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USW AREA ANALOGS

by

Keith Everett

June 2005

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13. ABSTRACT (maximum 200 words)

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USW AREA ANALOGS

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LIST OF ACRONYMS AND ABBREVIATIONS

ArcGIS	A suite of ESRI Geographic Information Systems software
ArcMap	An ESRI Geographic Information Systems computer program
ASCII	American Standard Code for Information Interchange
AUTEC	Atlantic Undersea Test and Evaluation Center
AXBT	Air launched Expendable Bathythermograph
C	A programming language
CalCOFI	California Oceanic Cooperative Fisheries Investigations
CASS/GRAB	An active sonar propagation loss model
CBLUG	Consolidated Bottom-Loss Upgrade
CPOAS	Cherry Point Operating Areas
CSDS 12	Commander Submarine Development Squadron Twelve
CTD	Conductivity/Temperature/Depth probe
DBDB5	Digital Bathymetric DataBase – 5 minute resolution
DBDBV	Digital Bathymetric DataBase – Variable resolution
DI	Directivity Index
DT	Detection Threshold
ESA	Environmental Site Analyzer
ESRI	A GIS and mapping software company
FORTRAN	A programming language
Gamma	The rate of change of sound velocity with depth
GDEM	Generalized Digital Environmental Model
GIS	Geographic Information Systems
GOEDAS	Geophysical Data System

GTSPP	Global Temperature-Salinity Profile Program
HFBL	High Frequency Bottom Loss
HFEVA	High Frequency Environmental Acoustics
HITS	Historical Temporal Shipping
HXBT	Helicopter launched Expendable Bathythermograph
ICECAP	An arctic ice database
ILD	Isothermal Layer Depth
ISR	Intelligence, Surveillance and Reconnaissance
JAXOAS	Jacksonville Operating Areas
km	Kilometers
LFBL	Low Frequency Bottom Loss
m	Meter
MATLAB	The MATLAB scientific programming language
METOC	Navy Meteorology and Oceanography community
MIW	Mine Warfare
MLBO	Mine-Like Bottom Object
MLD	Mixed Layer Depth
MODAS	Modular Ocean Data Assimilation System
MOODS	Master Oceanographic Observation Data Set
NaN	Not a Number
NAVOCEANO	Naval Oceanographic Office
NGA	National Geospatial-Intelligence Agency
NGDC	National Geophysical Data Center
NL	Noise Level
NMLD	Naval Research Laboratory Mixed Layer Depth

NOAA	National Oceanic and Atmospheric Administration
NODC	National Ocean Data Center
NOMBO	Non-Mine Bottom Object
NOS	National Ocean Service
NOSHDB	National Ocean Service Hydrographic Data Base
NPMOC	Naval Pacific Meteorology and Oceanography Center
NRL	Naval Research Laboratory
NSW	Naval Special Warfare
OAML	Oceanographic and Atmospheric Master Library
OCSEAP	Outer Continental Shelf Environmental Assessment Program
OPAREAS	U.S. Fleet Operating Areas
PCIMAT	Interactive Multisensor Analysis Trainer for the Personal Computer
RL	Reverberation Level
SID	Systems Integration Division
sec	Second
SIPRNET	Secret Internet Protocol Router Network
SL	Source Level
SN	Shipping Noise
SNR	Signal to Noise Ratio
SPECOP	Special Operation
SSXBT	Submarine launched Expendable Bathythermograph
SSXSV	Submarine launched Expendable Sound Velocity Probe
SUW	Surface Undersea Warfare
SV	Sound Velocity

SVP	Sound Velocity Profile
TACMEMO	Tactical Memorandum
TDA	Tactical Decision Aid
TL	Transmission Loss
TS	Target Strength
TWTT	Two Way Travel Time
U.S.	United States
USW	Undersea Warfare
VCOAS	Virginia Capes Operating Areas
VSS	Volume Scattering Strength
WOA01	World Ocean Atlas 2001
WOD	World Ocean Data
WOD01	World Ocean Database 2001
WRN	Wind and Residual Noise
XBT	Expendable Bathythermograph
XPTS	Expendable Pressure, Temperature and Salinity Probe
XSV	Expendable Sound Velocity Probe

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I. BACKGROUND AND APPLICABILITY

A. BACKGROUND

Finding ocean areas that are operationally similar is an age-old problem for the Navy. Whether it entails finding an area with the same winds or the same acoustic conditions, there has always been a need to train in areas as much like the areas the Navy fights in as possible. At first glance it would seem that the problem of finding two areas of ocean that are similar would be easy. But when the numbers of variables that effect submarine operations are taken into account, the problem grows considerably. How does one characterize the ocean in a meaningful way for all the various types of Undersea Warfare (USW) missions? The ocean parameters that are similar for deep-water USW tracking may be completely different for shallow water minefield penetration. Training for an under ice operation requires a skill set unlike any other and the environment must be characterized in a wholly different way for such a mission. Since the late 1980s, there have been several attempts to develop a systematic method to find "Analogous Operating Areas" using available databases and processing.

1. Process Background

Typically a manual, case-by-case approach to area comparison has been the order of the day for the past two decades. Several automated processes have been attempted in the last few years, including the Environmental Site Analyzer (ESA) developed by Bob Miyamoto and Bill Kooiman at the Applied Physics Laboratory at the University of Washington. These tools, although well suited for the specific tasks they were designed, usually do not have the inherent capacity to be used for the broad range of applications for which a submariner would apply them.

There are two basic mathematical approaches used for comparing sets of parameters in any application. One is to develop a weighting algorithm that expresses the environment in terms of a series of parameters that are weighted and summed to express similarity. This approach is good for mathematical comparisons. The other basic approach is to use a series of heuristic rules to produce a dichotomous grouping of similar sets, i.e. a decision tree. This approach will yield specifically similar sets, but it is not well suited for mathematical methods. The best approach may be to use a combination of the two. A series of simple logic rules are used to narrow the field of choices and then the weighting factors are used to determine a best fit from the smaller set. The ESA uses this combined approach. The ESA uses fuzzy logic to determine weights based on environmental characteristics like Sound Velocity Profile (SVP) and bottom characteristic and then applies heuristic rules to adjust these weights according to a set of SVP types (Miyamoto, 1999). A more robust product would also have to use rules for comparison based on the type of operation being considered. For example, it would have to weight reverberation level for active sonar search, but this parameter would carry much less weight for passive sonar. Fuzzy logic is a relatively new mathematical discipline that attempts to formalize a "common sense" problem solving approach using a series of simple statements. It will be discussed in more detail in Chapter IV.

2. Database Background

There are currently well populated and well resolved databases for SVPs worldwide. The one used most often for current Tactical Decision Aids (TDAs) in the fleet is the Generalized Digital Environmental Model (GDEM). This provides monthly and seasonally averaged SVPs for most of the ocean at scales as small as 10 arc minutes. There are similar databases available for sea surface weather climatology (wind and rain for ambient noise), shipping densities, bathymetry and bottom type. While many of these databases may be adequate for analog determination, other factors like bioluminescent properties and mine like bottom object densities are not well documented in the geospatial or temporal sense. Some are not even well understood in theory. There are also limitations within databases like GDEM because certain important acoustic parameters like ocean Mixed Layer Depth (MLD) are characterized on a monthly time scale and half a degree horizontal scale, so they may not represent a typical SVP for any given day. In general, the less conventional the USW mission, the less likely the parameters required to match areas will be well documented. For example, information for under ice operations about ice keel depths and distribution has not been maintained in recent years. The initial stages of this project were research into what operationally significant data is available.

B. APPLICABILITY

Admiral McGee in his 2005 “Enterprise Strategy” for the Navy METOC community, states that the highest priority business lines in the community are Anti-Submarine Warfare, Naval Special Warfare (NSW), Mine Warfare (MIW), and Intelligence, Surveillance and Reconnaissance (ISR) (McGee, 2005). All of these missions require accurate and precise ocean acoustic and environmental prediction and evaluation. Having a training area as physically similar as possible to the actual operational area will be critical to proper fleet preparation and will aid in TDA development.

This research topic is also responsive to fleet concerns for Analogous Operating Areas via a Submarine Development Squadron Twelve (CSDS 12) Tactical Development and Evaluation Memorandum (Commander Submarine Development Squadron Twelve, 2004). It will specifically address the requirements of the Submarine Force via feedback from CSDS 12 and the Naval Warfare Development Center. The intent of this research project is that a TDA or Tactical Memorandum (TACMEMO) could be easily developed from the final results.

C. OUTLINE

The general organization, by chapter, of the thesis is: provide background, describe the data used to characterize the environment and the databases available to do so, describe the characterization of the environment in a meaningful way using the data available, outline data analysis methodologies, describe the case study used to investigate the data analysis methodologies and conclude with a review of the thesis and recommendations for follow on research. In parallel with the research into the data and methods used, programming code in the MATLAB scientific language and data manipulation and display in the ESRI ArcMap environment will be completed in order to test the methodologies and provide a means to produce the test case. This programming process is an integral part of the project and will, along with the data sets, be the primary product used to advance this project in follow on theses.

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II. AVAILABLE DATA

A. THEORY OF DATA REQUIRED

In theory the process of environmental characterization must be approached in terms of the type of delectability considered. Acoustic detection is described by the passive and active sonar equations (Urick, 1983, p. 29):

Active Sonar Equations:

Noise Background Limited

$$SL - 2TL + TS = NL - DI + DT_N$$

Reverberation Background Limited

$$SL - 2TL + TS = RL + DT_R$$

Passive Sonar Equation

$$SL - TL = NL - DI + DT_N$$

SL = Source Level. For active sonar, SL is defined as the intensity of sound radiated by a projector (Urick, 1983, p. 71). For passive sonar, SL is defined as the intensity of the noise radiated to a distance by an underwater source (Urick, 1983, pp. 328-329). Both are normally defined at an arbitrary distance of 1 m from the source.

TL = Transmission Loss. TL is defined as a quantitative description of the loss of intensity of sound between a point 1 m from the source and a point at a distance (Urick, 1983, p. 99). For active sonar, transmission loss is doubled because the sound travels from the source to the target and back from the target to the source.

TS = Target Strength. TS is defined as the intensity of an echo returned from an underwater object in relation to the incident sound intensity, i.e. the ability of a target to reflect sound energy (Urick, 1983, p. 291).

DI = Directivity Index. DI is an expression of array gain in terms of the directional functions of signal and noise (Urick, 1983, p. 42).

NL = Noise Level. NL is defined as that part of the total noise background that is not from an identifiable source. It has two constituents: the noise which is due to the hydrophone and its mounting, called "self-noise", and that due to the environment, called "ambient noise" (Urick, 1983, p. 202).

RL = Reverberation Level. RL is defined as the sum total of all scattering from discontinuities in the physical properties of the ocean. It represents the echo level of the return from environmental elements. These elements include volume scattering from, marine life and inanimate matter in the ocean. Other elements include sea surface scattering and ocean bottom scattering (Urick, 1983, pp. 237-238).

DT = Detection Threshold. The DT is defined as the ratio of signal power to noise power measured at the receiver that is required for detection at some pre-assigned level of correctness (Urick, 1983, pp. 738-739). In simpler terms, it is the level of sound above the background that must be present for an operator to "detect" the signal.

The sonar equations represent the relationship between the desired portion of the acoustic field, the signal, and the undesired portion, the background noise or reverberation (Urick, 1983, p. 23). As such, they express the Signal to Noise Ratio (SNR). Source Level, Target Strength, Directivity Index and Self-Noise Level are source or target dependant, so they are not affected by the environment. The environmentally dependant factors are discussed below.

Transmission Loss includes spreading and attenuation. Spreading is a geometric effect representing the regular weakening of a sound signal as it spreads from the source. Attenuation includes losses due to absorption and scattering. Absorption is due to the conversion of sound energy to heat. Scattering is a process similar to that described in the discussion of RL above but represents sound energy that does not propagate to the receiver (Urick, 1983, p. 100). Significant factors which contribute to TL are the length of the acoustic path, which affects losses due to spreading and attenuation, and the discontinuities along that path, which affect volume scattering, surface scattering and bottom scattering. The acoustic path is highly variable and is determined by the Sound Velocity Profile (SVP) and ocean boundaries. Scattering is dependant upon the density and distribution of inhomogeneities in the water, the surface roughness and the bottom type and roughness.

Ambient noise is characterized by many factors including: shipping noise, biologic noise, wave and surf noise, rain noise, noise from seismic activity and industrial noise from, for example, oil drilling. All of these sources can be measured in-situ as the total ambient-noise. Some noise sources can the quantified by characterizing the noise sources themselves. For example, shipping noise can be correlated to shipping density.

In summary, the environmental factors which affect terms in the sonar equation are: SVP, bottom characteristics, amount of scattering material in the water, surface roughness and ambient-noise. The databases discussed below catalog and categorize these environmental factors. The example process in Chapter V focuses on the SVP and bottom characteristics.

Other non-acoustic factors affect operations. Visual factors include bioluminescence, water clarity and sea surface temperature (which affects infrared sensor performance). Atmospheric factors like atmospheric duct heights affect radar performance and detection. Having the ability to incorporate these types of non-acoustic features into the comparison process is a priority for future development.

B. DATA SOURCES AND TYPES

The approach taken toward the process of environmental characterization will be dictated in many ways by the format of the data. Therefore, an analysis of available data, its spatial and temporal distribution, its accuracy and resolution within the coverage area, and its format are important not only in data acquisition but also in the process formulation. For the purposes of this project, classified data sets will not be used, but these data sets will be referenced, because they will be necessary for the future analog area determinations.

A necessary choice for determining what data to use is whether it is unprocessed data or previously assimilated data that has already been processed or "gridded" into a uniform distribution. Well populated global databases are either extremely large geographically inhomogeneous sets of source data or smaller uniformly distributed derived products. Each has its advantages and disadvantages. Gridded data is error checked, formatted consistently and optimally interpolated for uniform horizontal, vertical and temporal spacing. Gridded data accuracy is dependant on the density and distribution of its source data. Unprocessed data usually contains errors, is not always complete, is not always consistently formatted, can be extensive and can have non-uniform distribution. Therefore, it usually requires more intensive processing to assimilate. However, the spatial and temporal resolution of unprocessed data can be much higher than gridded data. Gridded data was chosen for the example case study in Chapter V because it is already error checked and each SVP is complete, including bottom data.

The database list below is thorough but not completely comprehensive. It includes databases from the Naval Oceanographic Office (NAVOCEANO), the National Oceanic and Atmospheric Administration (NOAA) and some other international agencies that archive the primary acoustic parameters (SVP, bathymetry, bottom composition, background noise and scattering strength) (Urick, 1983, p. 19). Based on discussions with representatives of CSDS 12, other acoustic and USW operational parameters that are of concern to the fleet are included (Cooke et. al., 2004). Both NOAA and NAVOCEANO maintain other databases that could be used for future application including atmospheric radar propagation data. The data sets listed were chosen because they are U.S. government sponsored or supported, contain significant data and have global or regional coverage that includes both U.S. Fleet Operating Areas (OPAREAS) and routine deployment areas. Table 1 summarizes all the databases listed.

C. OAML

The Oceanographic and Atmospheric Master Library (OAML) is a set of standardized configurations for Navy oceanographic and atmospheric models and databases maintained by NAVOCEANO. Among the OAML standardized and maintained databases are the GDEM, DBDBV, CBLUG, LFBL, HFBL, VSS, WRN, SN, HITS and ICECAP data. All are available from NAVOCEANO on the SIPRNET at http://199.208.205.53/common/oaml.html and some are available open source as listed below (Naval Oceanographic Office Systems Integration Division [NAVOCEANO SID], 2004, p.1). The OAML databases are noted in the descriptions below. No classified data will be used in the example process in Chapter V.

D. ACOUSTIC DATA SOURCES

The USW environment is primarily an acoustic one. Accurately characterizing the way that sound will propagate in an area is the first and most important step in determining how to operate there.

1. Sound Velocity Profiles

More than any other characteristic, the SVP is critical to properly define the sound propagating properties of an area (Medwin and Clay, 1998, p. 4).

a. Unprocessed Data

WOD01

The National Ocean Data Center (NODC), a division of the NOAA, maintains the World Ocean Database 2001 (WOD01), which consists of unclassified unprocessed ocean data from many sources. These include Conductivity/Temperature/Depth (CTD) profiles from oceanographic research vessels and buoys, expendable bathythermographs launched from fixed and rotary winged aircraft, surface ships and submarines (XBT, AXBT, HXBT, SSXBT), other expendable probes that measure pressure, temperature, salinity or sound velocity (XSV, SSXSV, XPTS) and other biologic and chemical data not applicable to this project. It is available from an open source internet interface sorted by instrument type and by rectangular area, World Ocean Data (WOD) area or year at http://www.nodc.noaa.gov/OC5/WOD01/pr_wod01.html and http://www.nodc.noaa.gov/OC5/SELECT/dbsearch/dbsearch.html. Extensive metadata is included and there are pre-programmed executable extraction programs available on the website. Depth at the station, instrument type and accuracy data are not extracted by the pre-programmed code, but can be extracted. This data could be useful to determine standard deviation thresholds for statistical analysis or to eliminate the need for separate bathymetry data. Data are available at either observed depths or standard depths. The standard depth profiles have lower horizontal as well as lower vertical resolution, which makes MLD and thermohaline gradient determination more difficult. Spatial and temporal resolution is highly dependant on the data source and survey location. For example, off the coast of California, the California Oceanic Cooperative Fisheries Investigations (CalCOFI) data set is very robust in time resolution, but the spatial resolution is set based on predefined survey locations. The data sets of Expendable Bathythermograph (XBT) data are denser in OPAREAS (which is ideal since these are the areas that will be used for comparison) but are sparse in deployed areas (in this unclassified format). Coverage of U.S. coastal and exclusive economic zones is very good (National Ocean Data Center [NODC], 2005b).

MOODS

The Master Oceanographic Observation Data Set (MOODS) is administered by NAVOCEANO and is analogous to the WOD01 database. It contains over six million SVPs from Navy and other agency open source and classified sources up to SECRET. It is available from the NAVOCEANO classified data warehouse on the SIPRNET at http://199.208.205.53/index.html (Naval Oceanographic Office Classified Data Warehouse [NAVOCEANO], 2005a).

GTSPP

The Global Temperature-Salinity Profile Program (GTSPP) is an international program that houses unprocessed and quality checked (but not error corrected) temperature-salinity profiles from worldwide sources. Shipping lanes are the primary source locations, with ocean surveys making up the remainder of the data. The data set contains data submitted since 1990 and is organized monthly with significant metadata for reference. All unprocessed NODC data from the period 1990 to the present is contained in the GTSPP and the WOD01 data set contains all the GTSPP data up through the WOD01 publication. It is available open source via an internet interface at http://www.nodc.noaa.gov/GTSPP/gtspp-home.html. There are no preprogrammed extraction applications available, so the data is more difficult to access (Global Temperature-Salinity Profile Program [GTSPP], 2005).

b. Gridded Data

WOA01

NODC also has oceanographic derived products, including the World Ocean Atlas 2001 (WOA01). This is a one degree optimal interpolation of the WOD01 and is an updated version of the World Ocean Atlas 1998, popularly referred to as Levitus Data. Data and extraction executables are available at http://www.nodc.noaa.gov/OC5/WOA01/pr_woa01.html. SVPs are climatological by year, season or month. Data extraction is somewhat cumbersome since the data are extracted as separate files for each standard depth in each time period for each parameter. For example, monthly data includes 576 files for temperature and salinity. Monthly mean data have coverage to 1500 m depth, while seasonal and yearly mean data have coverage to 5500 m depth. A land/sea mask is also available at the same one degree resolution which gives sea floor depths. This is a good low resolution data set that could be used by itself for the process example, would be relatively easy to import into ArcMap and contains all the primary acoustic information for SVP evaluation. It could also supplement data for areas where the WOD01 data is sparse. Additional MATLAB code would still be required to derive sound velocity. Also, the vertical resolution is poor due to the use of standard depths (NODC, 2005a).

GDEM

The NAVOCEANO Generalized Digital Environmental Model (GDEM) has seasonal and monthly mean profiles for temperature, salinity and sound velocity with global coverage at varying spatial resolution from 10 to 30 arc minutes. It is derived from the MOODS data set. Some of the areas have very little source data and are therefore inherently less accurate. The monthly mean tends to average out the MLD since this is the most variable portion of the water column. The SVPs are in the standard depth format so, as with the standard depth WOD01 and WOA01 data, MLD and thermohaline gradient determination is less accurate. There is one great advantage to this data set – its merged SVPs extend to the bottom and the bottom depth is contained in the header for each profile. Sounding data is from the DBDBV database. The deep SVP and bottom depth can be used to supplement unprocessed data from other sources that does not extend to the bottom. For areas with little or no coverage in unprocessed data sets, this is good supplemental data. An OAML database, GDEM was derived from classified sources but is UNCLASSIFIED and is available open source from https://128.160.23.42/gdemv/gdemv.html. Data access is by point, great circle or rectangle (limited area per download), by month and in ASCII format similar to the WOD01 extracted data. Sound Velocity (SV) is already calculated. Unlike the WOA01 extracted data, complete SVPs for each location are together in the same file (NAVOCEANO SID, 2004, p. 15 and NAVOCEANO, 2005c). This is the database used in the example process described in Chapter V because the format is well defined, the data is easily extracted in ASCII format and the bathymetry data is imbedded in the data set.

MODAS

The Modular Ocean Data Assimilation System (MODAS) is an estimated SVP field based on satellite sea surface temperatures (SST) and sea surface height from satellite infrared and altimetry data merged with the GDEM database. It is at the same resolution and accuracy as the root database. This is a near real time model, or "Dynamic Climatology," of the ocean developed and administered by the Naval Research Laboratory (NRL). It is not usually used for climatological studies but archived data is available open source at http://www7300.nrlssc.navy.mil/altimetry/. Using archived MODAS data on a shorter time scale than GDEM would give improved temporal resolution with consistent spatial coverage and integrated sounding data. MODAS still has the lower vertical resolution of the standard depth convention (Naval Research Laboratory [NRL] Division 7300, 2005).

NMLD

The Naval Research Laboratory (NRL) Mixed Layer Depth (NMLD) Climatology is a one degree resolution monthly mean climatology of the Isothermal Layer Depth (ILD) and Mixed Layer Depth (MLD). It is derived from the World Ocean Atlas 1994 (Levitus) using an algorithm for temperature and density to provide optimal MLD. The data set, with FORTRAN extraction code, and FORTRAN code of the algorithm are available open source from the NRL website http://www7320.nrlssc.navy.mil/nmld/nmld.html. The NMLD code is described as robust and capable of processing data at vertical resolutions greater than the Levitus Set (NRL Code 7304, 2005). The algorithm is discussed in more detail in Chapter III.

2. Bathymetry

a. Unprocessed Data

NGDC Marine Trackline Geophysics Database

NOAA's National Geophysical Data Center (NGDC) Marine Trackline Geophysics database contains bathymetric data collected from 1953 to the present. Worldwide coverage from sources including both U.S. and foreign institutions and government agencies constitutes the most comprehensive unprocessed hydrographic data set available from NOAA. The data set is accessible in limited area files via an open source internet interface at http://www.ngdc.noaa.gov/mgg/geodas/trackline.html or on

DVD-ROM for $75. Free software is available for extraction to xyz ASCII and ArcGIS data files. The GEOphysical DAta System (GOEDAS) is the extraction software and is used for most of NGDC's data (National Geophysical Data Center [NGDC]).

NOSHDB

NOAA's National Ocean Service (NOS) Hydrographic Data Base (NOSHDB) provides the majority of all the hydrographic survey data for the coastal U.S. This is all the unprocessed U.S. coastal bathymetry data from every survey held by NOAA since 1851. NOSHDB also contains data from the National Geospatial-Intelligence Agency (NGA) and foreign sources. NOSHDB is accessible via GOEDAS at http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html or on DVD-ROM for $75 (NOS, 2005).

b. Gridded Data

ETOPO5

ETOPO5 is a NGDC gridded 5 minute land and sea-floor elevation database compiled in 1988 from various other databases. This lower resolution database has been superseded by the ETOPO2 database, but some older versions of TDAs still use ETOPO5 (NGDC, 2005a).

ETOPO2

ETOPO2 is the newest NGDC gridded database with a resolution of 2 minutes. This data set is a combination of several others including DBDBV, DBDB5, the GLOBE one minute land survey and several surveys utilizing global seafloor topography from satellite altimetry. This is probably the best open source data set available of gridded ocean depth data for modeling. It is important to note that the majority of the data for ETOPO2 was derived from remote sensing sources and not from hydrographic surveys. The satellite altimetry was used in conjunction with sparse hydrographic data to interpolate the sea floor topography from gravity anomalies and is only accurate enough for survey planning and ocean modeling, but not for navigational safety. ETOPO2 is accessible via GOEDAS at http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html or on CD-ROM for $75 (NGDC, 2005a).

NGDC Coastal Relief Model

NOAA's National Geophysical Data Center (NGDC) Coastal Relief Model is the gridded data set derived from the NOSHDB and other government and private sources. Coverage is for U.S. coastal waters. This 3 sec open source model is available in limited area files via GOEDAS at http://www.ngdc.noaa.gov/mgg/coastal/coastal.html or on DVD-ROM for $75. The resolution of this set is higher than any available gridded SVP data and is therefore not useful for the USW acoustics in the case study for this thesis. It would be more useful for determining unique bottom features and for other MIW applications. Processing this data in a meaningful way for MIW would be a topic for follow on theses (NGDC, 2005b).

DBDBV

The Digital Bathymetric DataBase – Variable resolution (DBDBV) provides ocean floor depths at gridded resolutions of 5, 2, 1 and 0.5 minutes. This NAVOCEANO OAML database is available in various formats including simple yxz ASCII text and ArcGIS formats from their open source data warehouse at https://128.160.23.42/dbdbv/dbvquery.html. DBDBV is the continuation of the DBDB5 five minute database, which was a computer interpolation of existing charts of ocean basins. DBDBV is also an interpolation but at higher resolutions in certain areas and was designed for use in modeling applications and general contour mapping (NAVOCEANO SID, 2005b).

3. Bottom Characteristics

a. Unprocessed Data

MIW Bottom Types

The basis for most of the NAVOCEANO bottom data is a database of Enhanced Category bottom types with over 200 different provinces. There are two simplified data sets derived from the Enhanced Category database. The Standard Category set has 65 province types and the Reduced Category has 15. Since this data is in grids of province numbers and the province numbers are descriptive of the sediment type in geologic not acoustic terms, the comparison of two bottom areas has to be exact for correlation. A method of cross correlating province numbers to physically similar bottom types is required to determine cross category comparisons. All three category types have global coverage. These UNCLASSIFIED data sets are available from NAVOCEANO's classified data warehouse on the SIPRNET at http://199.208.205.53/index.html. (Coleman, 2005)

Seafloor Sediment Grain Size Database

The NGDC maintains a database of unprocessed seafloor grain size data from over 17,000 seafloor samples worldwide. Developed as part of the Outer Continental Shelf Environmental Assessment Program (OCSEAP), coverage is limited to continental shelf regions. It is available open source in tab delimited format from http://www.ngdc.noaa.gov/mgg/geology/size.html (NGDC, 2005c).

b. Gridded Data

NGDC Sediment Thickness

NGDC has recently compiled a set of data for the total sediment thickness of the world's oceans and marginal seas outside the arctic. The sediment thickness is a gridded 5 minute resolution contour derived from hydrographic surveys and based on an assumed single layer constant density sediment layer. It is available from NGDC in MATLAB friendly NaN coded xyz ASCII format and in ArcGIS layer format at http://www.ngdc.noaa.gov/mgg/sedthick/sedthick.html. Because it is gridded at a different resolution than GDEM and easily downloaded in ASCII format, this is the bottom characteristic used for the case study in Chapter V (NGDC, 2005d).

LFBL

Low Frequency Bottom Loss (LFBL) is a gridded global acoustic bottom interaction model with inputs from unprocessed NAVOCEANO classified data. An OAML database, it is classified CONFIDENTIAL. Extensive data for each segment includes sediment characteristics and provinces for low frequencies including sediment densities and sediment sound speeds for multiple layers. Extraction software is available in C code. The majority of the world is at 5 minute resolution with 12 second resolution for some overseas areas (NAVOCEANO SID, 2001c).

LFBL Sediment Thickness

Within the LFBL database there is an UNCLASSIFIED sediment thickness database with 5 minute resolution. Similar to the NGDC sediment thickness, it is available from NAVOCEANO's classified data warehouse (NAVOCEANO, 2005a).

CBLUG

The LFBL data set has become increasingly precise in its characterization of bottom acoustic interactions and now has over 800 provinces. With this increased precision, LFBL has become less user friendly for the fleet and NAVOCEANO has consolidated LFBL data into a set of nine general bottom categories called the Consolidated Bottom-Loss Upgrade (CBLUG) database. This puts the number of data types equal to those in HFBL and allows similar coding for data manipulation. An OAML database, it is classified CONFIDENTIAL (NAVOCEANO SID, 2004, p.17).

HFBL

High Frequency Bottom Loss (HFBL) is a gridded global acoustic database with 5 minute resolution for the majority of the world and 6 seconds in one overseas area. It is classified CONFIDENTIAL and consists of high frequency bottom loss provinces using nine standard Navy bottom loss curves. The Curves are displayed in Figure 1. Extraction software is available in C code. HFBL is an OAML database (NAVOCEANO CID, 2001b).

HFEVA

The High Frequency Environmental Acoustics (HFEVA) data set is another CONFIDENTIAL data set from the NAVOCEANO classified data warehouse and is the standard for MIW applications. It is used in the Mine Warfare Environmental Decision Aids Library (MEDAL) and for the CASS/GRAB model for TDAs (Coleman, 2005).

4. Ambient Noise

a. Gridded Data

Shipping Noise

NAVOCEANO maintains a CONFIDENTIAL database of ambient noise gridded at 5 minutes resolution and climatologically by month. "Shipping Noise" is a misnomer because the database consists of an estimation of the ambient noise, not just shipping noise. It is a compilation of several databases, Shipping Noise (SN) includes a primarily 300 Hz and lower-omni directional ambient noise database, low and high resolution low frequency databases for 50 Hz omni-directional noise, historical ice edge data and 50 Hz directional noise. The files are available individually by region and month for the northern hemisphere. This is an OAML database (NAVOCEANO SID, 2004, p.18).

WRN

The Wind and Residual Noise (WRN) database is a CONFIDENTIAL set of gridded provinces for spectral wind class and other ambient noise sources. These other noise sources include Sperm and Baleen whale provinces and a flag for the presence of oil rigs. An OAML database, it has a resolution of 2 to 5 minutes and is tabulated by month. Coverage is for the northern hemisphere excluding the arctic. This data set also includes an UNCLASSIFIED wind noise spectral table, Table 2, which can be used to evaluate frequency dependence of climatologic winds from other sources (NAVOCEANO SID, 1993).

HITS

The Historical Temporal Shipping (HITS) database is a gridded 1 degree set of shipping densities for ship types in five categories tabulated by month. It is UNCLASSIFIED and simply lists the average number of each type of ship per month per 1000 square nautical mile area. HITS data can be operational descriptors for comparison in missions like ISR or a relative measure for ambient noise. For the purposes of a comparison algorithm, shipping density can be used as a descriptor of the actual noise level with no additional acoustic modeling. HITS does not contain any data on naval vessels, passenger ships or ships less than 18 m in length. HITS is a global OAML database (NAVOCEANO SID, 2004, p. 16)

Surface Marine Gridded Climatology

NAVOCEANO maintains a global one degree gridded baseline climatology for model use. The Surface Marine Gridded Climatology database contains sea level pressure, wind speed (on eight points of the compass), air temperature, dewpoint, sea surface temperature, air-sea temperature difference, wave height, percent frequency of gale force winds and icing potential information. Some of this data is useful for acoustic considerations, like wind forcing and wind/wave noise, and others for general operations and ISR mission parameters. An OAML database it is UNCLASSIFIED (NAVOCEANO SID, 2004, p. 20).

5. Scattering Strength

a. Gridded Data

VSS

The NAVOCEANO Volume Scattering Strength (VSS) database is a CONFIDENTIAL gridded 5 degree resolution data set with global coverage except in the Antarctic. Tabulated by month, it contains provinces for day and night scattering strength and other frequency specific data about the deep scattering layer including depth (NAVOCEANO SID, 2004, p. 19).

E. VISUAL DATABASES

1. Bioluminescence

NAVOCEANO maintains an unprocessed database of bioluminescence information from various sources. A regional database, it is classified up to SECRET and is available from the NAVOCEANO classified data warehouse. It is a collection of over 4000 individual track files from research cruises (NAVOCEANO, 2005a).

2. Secchi Depths

A Secchi disk is a white opaque disk that is used to asses water clarity by measuring how deep it can be submerged and still be seen with the naked eye. Secchi depths are a standard measure of water clarity and are a useful measure for submarine visual counterdetection. NAVOCEANO maintains a Restricted database of unprocessed Secchi Depths with regional coverage which is available from their classified data warehouse. Like the bioluminescence data, it is a collection of individual track files, resulting in sparse coverage for many areas (NAVOCEANO, 2005a).

F. OTHER OPERATIONAL DATABASES

1. MLBO Density

The Mine-Like Bottom Object (MLBO) or Non-Mine Bottom Object (NOMBO) density is cataloged by NAVOCEANO in CONFIDENTIAL sets of various data types including side scan sonar images and density data in objects per unit area. Only available in a few sensitive areas, this data would not be useful for deployed areas, where it has not been compiled. (Coleman, 2005).

2. SPECOP Near-Shore Features

NAVOCEANO maintains a data set of non-technical noun name data for Special Operations (SPECOPs) and amphibious operations that include man made features (mud, gravel, boulders, etc.). This may be useful for future projects that use SPECOP mission profiles. SPECOP Near-Shore data is available upon request from NAVOCEANO via their classified data warehouse (Coleman, 2005).

3. ICECAP

ICECAP is an UNCLASSIFIED database for seasonal ice keel and ice draft statistics, but it has not been updated since 1991. Designed primarily for acoustic ice loss models, it is gridded at 60 nm resolution with coverage in the Arctic. ICECAP is an OAML database (NAVOCEANO SID, 2004, p. 16).

G. UNIQUE ACOUSTIC FEATURES

There are several unique undersea environmental features, like solitons or fresh water pockets, which can dramatically affect acoustic propagation as well as submarine operations. There is no database from either NAVOCEANO or NOAA that has these types of unique phenomena specifically cataloged. Most comparisons of these uncommon events are anecdotal and not well documented in open sources. In order to characterize these uncommon or unique features a new database would have to be created. Since the architecture of the process outlined in this project is designed from the start to be open, adding descriptions of unusual features like these is possible. Examples are listed below.

1. Internal Waves

Solitons are massive non-linear internal waves which often propagate along the thermocline and cause large rapid changes in mixed layer depth on the order of hundreds of feet in a few minutes. They are a documented phenomenon in the South China Sea, Sulu Sea and Andaman Sea, but are not seen in similar magnitude in other ocean areas (Alpers et al., 2005, Apel et al., 1985, p. 1625, Hsu and Liu, 2000, p. 72). Their effects on both sonar performance and submarine buoyancy are dramatic. There are similar mechanisms, which cause large internal waves in regions of fresh water inflow like that off the Columbia River in Washington State or near saline gradients like those in the straits of Gibraltar.

2. Fresh Water Pockets

Under ice there can be pockets of fresh water from melting ice or pockets of relatively saline water due to the formation of sea ice. Like freshwater near the mouth of rivers these saline gradients can dramatically affect acoustics and submarine performance.

H. PCIMAT

The Interactive Multisensor Analysis Trainer for the Personal Computer (PCIMAT) is the primary TDA for acoustic modeling in the fleet and is used in this project to verify the test case. PCIMAT uses SVPs from GDEM, DBDBV or ETOPO2 bathymetry and LFBL bottom characteristics to model range independent and range dependent propagation losses. Because PCIMAT uses the same SVP database as the example process in Chapter V, PCIMAT is used to evaluate the example process output.

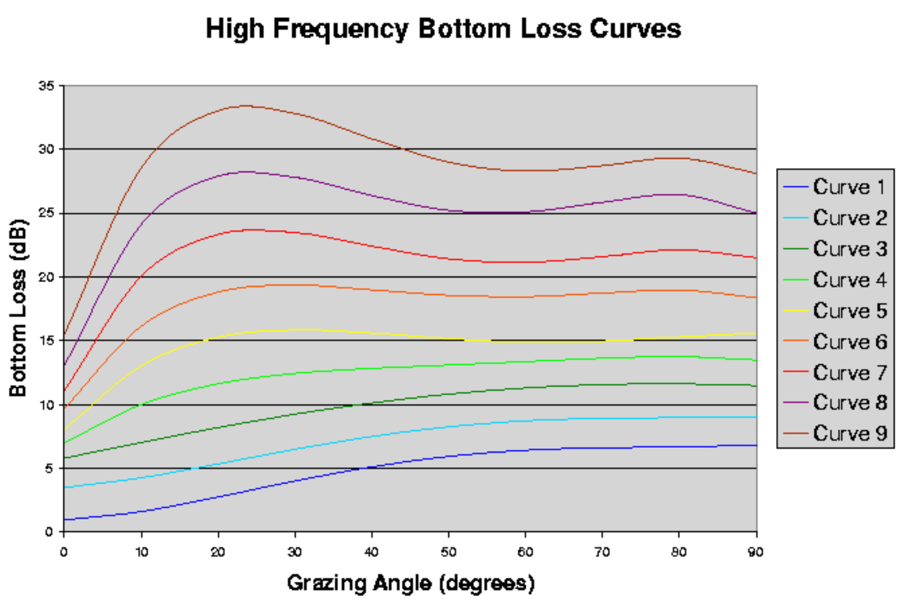

Figure 1. High Frequency Bottom Loss Curves. [From NAVOCEANO SID, 2001a].

Database	Source	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Classification
SVP					
Unprocessed Data					
WOD01	NODC	N/A	Observed	N/A	UNCLASS
MOODS	NAVOCEANO	N/A	Observed	N/A	Up to SECRET
GTSPP	GTSPP	N/A	Observed	N/A	UNCLASS
Gridded					
WOA01	NODC	1 degree	Standard	Monthly	UNCLASS
GDEM	NAVOCEANO	10-30 minutes	Standard	Monthly	UNCLASS
MODAS	NAVOCEANO	10-30 minutes	Standard	Daily	UNCLASS
NMLD	NRL	1 degree	Standard	Monthly	UNCLASS
Bathymetry	**Source**	**Horizontal Resolution**	**Coverage**		**Classification**
Unprocessed Data					
NGDC Trackline	NGDC		Global		UNCLASS
NOSHDB	NOS		US Coastal		UNCLASS
Gridded					
ETOPO5	NGDC	5 minutes	Global		UNCLASS
ETOPO2	NGDC	2 minutes	Global		UNCLASS
NGDC Coastal	NGDC	3 sec	US Coastal		UNCLASS
DBDBV	NAVOCEANO	0.5-5 minutes	Global		UNCLASS
Bottom Characteristics					
Unprocessed Data					
NODC Bottom Grain Size	NODC		Global		UNCLASS
MIW Bottom Types					
Enhanced Category	NAVOCEANO		Global	200+ provinces	UNCLASS
Standard Category	NAVOCEANO		Global	65 provinces	UNCLASS
Reduced Category	NAVOCEANO		Global	15 provinces	UNCLASS
Gridded					
NGDC Sediment Thickness	NGDC	5 minutes	Global		UNCLASS
LFBL	NAVOCEANO	5 minutes-12 seconds	Global		CONFIDENTIAL
LFBL Sediment Thickness	NAVOCEANO	5 minutes	Global		UNCLASS
CBLUG	NAVOCEANO	5 minutes	Global		CONFIDENTIAL
HFBL	NAVOCEANO	5 minutes	Global		CONFIDENTIAL
HFEVA	NAVOCEANO	Various	Global		CONFIDENTIAL
Ambient Noise					
Shipping Noise	NAVOCEANO	5 minutes	NH		CONFIDENTIAL
WRN	NAVOCEANO	2-5 minutes	NH		CONFIDENTIAL

HITS	**NAVOCEANO**	**1 degree**	**Global**		**UNCLASS**
Surface Gridded Climatology	**NAVOCEANO**	**1 degree**	**Global**		**UNCLASS**
Scattering Strength					
VSS	**NAVOCEANO**	**5 degree**	**Global**		**CONFIDENTIAL**
Visual					
Bioluminescence	**NAVOCEANO**	**Unprocessed**	**Regional**		**Up to SECRET**
Secchi Depths	**NAVOCEANO**	**Unprocessed**	**Regional**		**Restricted**
Other Operational Databases					
MLBO Density	**NAVOCEANO**	**Various**	**Regional**		**CONFIDENTIAL**
SPECOP Shore	**NAVOCEANO**	**Various**	**Regional**		**Up to SECRET**
ICECAP	**NAVOCEANO**	**60 nm^2**	**Arctic**		**UNCLASS**

Table 1. Summary of Databases. Listed in the order discussed in the chapter.

UNCLASSIFIED

Frequency (Hz)	Wind Speed (kn)											
	2	5	10	15	20	25	30	35	40	45	50	100
	Noise Level (dB)											
25	51.0	54.5	59.0	60.8	62.0	66.9	70.9	73.1	75.0	77.1	79.0	84.0
50	51.0	54.5	59.0	60.8	62.0	66.9	70.9	73.1	75.0	76.9	78.7	83.7
63	51.0	54.5	59.5	61.5	63.0	67.3	70.9	73.0	74.8	76.6	78.3	83.3
80	51.0	55.0	59.5	61.8	63.5	67.6	70.9	72.8	74.5	76.3	77.9	82.9
100	51.0	55.0	60.0	62.3	64.0	67.8	70.9	72.7	74.3	76.0	77.5	82.5
125	51.0	55.5	60.0	62.9	65.0	68.2	70.9	72.6	74.1	75.7	77.1	82.1
160	50.5	56.0	60.5	63.4	65.5	68.5	70.9	72.5	73.9	75.4	76.8	81.8
200	50.5	56.0	60.5	63.7	66.0	68.7	70.9	72.4	73.7	75.2	76.5	81.5
250	50.0	56.0	61.0	63.9	66.0	68.7	70.9	72.3	73.6	75.1	76.4	80.4
315	49.5	56.5	61.0	63.9	66.0	68.7	70.9	72.3	73.5	75.0	76.3	80.3
400	49.0	56.0	61.5	64.1	66.0	68.7	70.9	72.1	73.2	74.8	76.2	80.2
500	48.0	56.0	61.0	63.9	66.0	68.6	70.8	71.9	72.8	74.4	75.8	79.8
630	47.0	55.0	60.5	63.4	65.5	68.3	70.5	71.5	72.3	73.9	75.3	79.3
800	45.5	54.0	59.5	62.7	65.0	67.8	70.0	71.0	71.8	73.4	74.8	78.8
1000	44.0	52.5	58.5	62.0	64.5	67.2	69.4	70.4	71.2	72.7	74.0	78.0
1250	43.0	51.5	57.5	61.0	63.5	66.3	68.5	69.5	70.3	71.7	73.0	77.0
1600	41.5	50.0	56.5	59.7	62.0	64.9	67.3	68.3	69.1	70.4	71.5	76.5
2000	40.0	48.5	55.0	58.5	61.0	63.8	66.0	67.0	67.8	68.7	69.5	74.5
2500	38.5	46.5	53.5	57.0	59.5	62.2	64.4	65.4	66.2	67.4	68.0	73.0
3150	36.0	45.0	51.5	55.0	57.5	60.3	62.6	63.6	64.4	65.2	66.0	71.0
4000	34.0	42.5	49.0	52.5	55.0	58.1	60.7	61.7	62.5	63.0	63.5	68.5
5000	32.5	40.5	47.5	51.0	53.5	56.5	59.0	60.0	60.8	61.4	62.0	67.0
6000	31.3	39.3	46.3	49.8	52.3	55.3	57.8	58.8	59.6	59.7	60.4	65.4
10000	27.5	35.7	42.5	46.5	48.0	52.0	54.2	55.2	56.0	56.5	56.7	61.5
15000	24.0	33.2	39.8	43.8	46.5	49.5	51.5	52.4	52.9	53.4	53.7	58.5

UNCLASSIFIED

Table 2. Wind Generated Noise. Frequency in Hertz versus wind speed in knots with noise level in dB. [From NAVOCEANO SID, 1993].

III. EXAMINATION OF THE TACTICAL APPLICABILITY OF ACOUSTIC DATA

A critical step in characterizing the acoustic environment is to describe the Sound Velocity Profile (SVP) or Sound Speed Profile (SSP). SSP is probably the most accurate acronym since velocity includes a direction and the profile does not in fact give the direction, but the Navy often uses the SVP acronym convention. SVP will be used throughout the text and its inaccuracy noted here. How sound travels is dependent primarily on the path of the wave front, which is determined by the SVP (Medwin and Clay, 1998, pp.5-6).

Another important consideration is bottom interaction. This is characterized in the available data by the bottom depth, Low Frequency Bottom Loss (LFBL), High Frequency Bottom Loss (HFBL), sediment thickness, bottom grain size and Mine Warfare Bottom Type. The other boundary interaction at the ocean surface is characterized by ocean surface roughness. Climatological wind data can be used to estimate wave height distributions to describe surface roughness.

The Volume Scattering Strength (VSS) characterizes sound interaction with volume inhomogeneities. For passive applications it affects transmission loss. For active applications VSS affects transmission loss for the noise limited case and reverberation level for the reverberation limited case (Urick 1983, p. 21).

As discussed in Chapter II, the ambient noise level is characterized by both noise level descriptions like Shipping Noise and by descriptive data like HITS.

A. SOUND VELOCITY PROFILES

Several methods can be used for characterizing a SVP: (1) A very simple method is to look at a few key parameters for comparison like Mixed Layer Depth and the Deep Sound Channel Axis, but this is inadequate to describe ocean acoustic propagation. (2) A simple point-by-point comparison that determines a match based the number of common points between two profiles could be used, but a simple bias error between two otherwise similar profiles would produce poor a match with this method. (3) SVPs could be categorized by SVP types. The ESA uses nine basic SVP categories listed in Table 3

(Miyamoto, 1999). Each SVP within an area is classified by only one of these categories and the number of SVPs in the area within each category is used to assign fuzzy logic set membership for the area. These classifications represent the general types of SVPs that are seen in shallow water (on or near the continental shelf break with bottom depths of less than approximately 100 fathoms or 200 m). For deep water, the SVP is too complex to be characterized in this simple way. Additional parameters must be developed to account for this complexity.

ISOVELOCITY	Max – Min < 2 m/s
UPWARD REFRACTING	Min at surface and Max at bottom
CHANNEL	Min not at surface or bottom
DEEP LAYER	Max > 200 ft
INTERMEDIATE LAYER	75 ft < Max < 200 ft
SHALLOW LAYER	25 ft < Max < 75 ft
MILDLY DOWNWARD REFRACTING	Max < 25 ft and slope below MLD < 0.05
INTERMEDIATE DOWNWARD REFRACTING	Max < 25 ft and 0.05 < slope < 0.1
STEEP DOWNWARD REFRACTING	Max < 25 ft and slope > 0.1

Table 3. Environmental Site Analyzer SVP Types. Max and Min refer to the maximum and minimum sound velocity in the profile. [From Miyamoto, 1999].

The following is a more thorough approach to describing a SVP using a set of descriptive parameters to define the significant features of the profile. The typical mid latitude deep water SVP will serve as a guide for this development. Shallow water and other special case profiles will be processed for comparison in a different manner.

The descriptive parameters outlined below were developed based on the format of available data and an analysis of the minimum amount of information required to convey the tactically significant acoustic character of a SVP. These parameters then become the fuzzy logic sets that are used to compare areas. The parameters are summarized on a diagram of a typical mid latitude SVP in Figure 2.

1. SVP Characterization

In this section, the SVP data is assumed to be in an unprocessed form with no temporal averaging and may contain anomalous data points. It is also assumed that the vertical resolution is higher than the standard depths used in GDEM data.

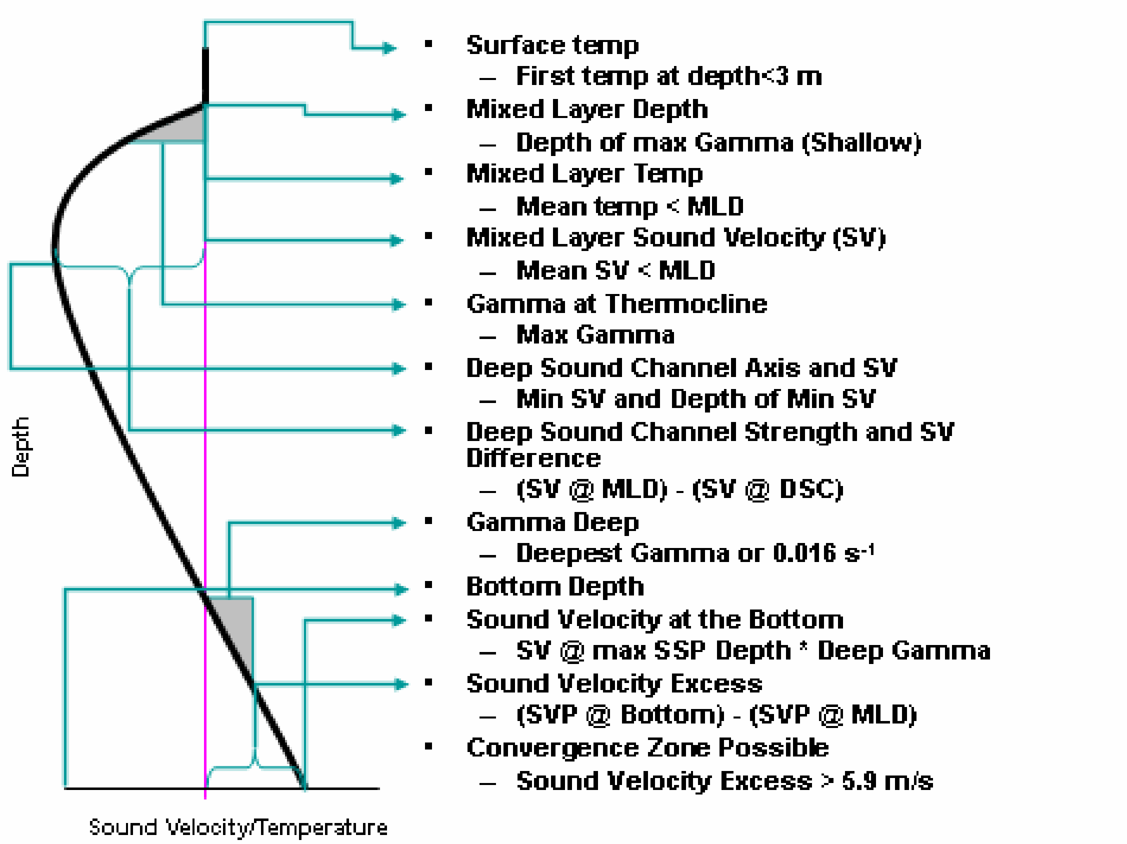

Figure 2. SVP Characterization Parameters.

a. Surface Temperature

Because not all data sets have data at a depth of zero, the shallowest temperature in the profile is used if this depth is less than three m. This parameter has some acoustic significance, is easily obtained, gives an indication of the climate of the area and is relevant to visual and infrared sensors.

b. Mixed Layer Depth (MLD)

Several methods of MLD determination are hypothesized below. They were tested in the processing of data from GDEM. The most promising is an algorithm in a FORTRAN program available from the Naval Research Laboratory (NRL) Mixed Layer Depth (NMLD) project (NRL Code 7304, 2005). A derivative of this algorithm is used in the example case in Chapter V. NMLD uses a deviation of temperature of 0.8 $^{\circ}C$ from the 10 m depth to determine Isothermal Layer Depth (ILD). It uses the same criteria for MLD except where there is a pronounced salinity gradient. In this case it uses a density deviation that is equivalent to a 0.8 C isohaline temperature change (NRL Code 7304, 2005). The 0.8 $^{\circ}C$ deviation in the NMLD method is based on a sensitivity analysis of ΔT for MLD determination in seasonal climatological data (Kara, Rockford and Hurlburt, 2000, p. 16,819). The test case in Chapter V uses the 0.8 $^{\circ}C$ deviation criteria for MLD determination because it provided accurate MLD determinations based on visual inspections of SVPs from the source and target areas. Because this method only uses depths greater than 10 m it has the disadvantage of always defining a MLD of 10 m even if one does not exists.

The gradient of SV can be used to find inflection points and the region of maximum sound velocity change. “Gamma” is defined as the rate of change in SV with depth: ${}^{dSV}\!/_{dDepth}$. Based on the assumption that the thermohaline layer has the maximum gamma, the Mixed Layer could be defined as the layer above this maximum in gamma. Quality checks are required for this method due to anomalous data points in the profile. As described in Figure 3, there may be more than one mixed layer, a decaying deeper mixed layer may have developed when the surface forcing and therefore mixing was stronger, which was not supported by the surface forcing when the profile was taken. On longer time scales, the multiple mixed layers are a transient and the algorithm should measure only the main thermocline. On shorter time scales, the algorithm should identify and characterize the multiple mixed layers. To discriminate against anomalous data points in the deep profile, the MLD should be shallow (less than 200 meters for example). To discriminate against anomalous data points in the shallow profile, the gamma should be consistently large for several depth increments below the MLD. For multiple mixed layers, the standard deviation could be used to check if the sound velocity (SV) in the mixed layer is consistent with a well mixed temperature and salinity. A running standard deviation that flags the depth at which the temperature and salinity begin to change significantly could also be used as a check.

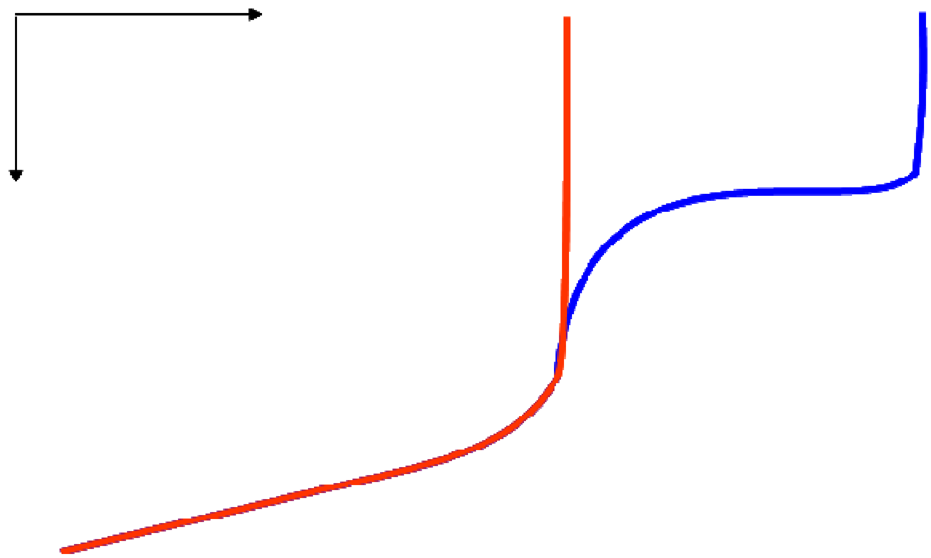

Figure 3. Example of Temperature vs. Depth for multiple mixed layers due to a change in surface forcing.
The red line represents a mixed layer that was developed due to strong surface forcing. The blue line represents a subsequent mixed layer, developed due to surface heating and less surface forcing.

A comparison of various SVPs from source and target areas using the calculated criteria above and a visual inspection of the plotted SVPs showed that the NMLD method was most consistent with the observed MLD. The standard deviation method tended to default to 30 m, regardless of the standard deviation value used to discriminate, and the maximum gamma was usually 10 – 50 m deeper than the NMLD MLD. This inspection was with error corrected, spatially averaged, temporally averaged profiles at standard depths and may not be consistent with higher resolution unprocessed data. When profiles with higher vertical resolution are incorporated into the process, a check of all these methods should be conducted.

Using appropriate values for sound velocity and velocity gradient, the low frequency cutoff for the mixed layer mathematically reduces to be proportional to the MLD (Urick, 1983, p. 151). Once determined, MLD is the entering argument for the next two analyses.

c. Mixed Layer Temperature

Mixed Layer Temperature is defined as the mean temperature above the MLD. This is not directly applicable to the acoustics but mixed layer temperature is readily obtained and is a physical description of the environment. Mixed layer temperature affects ships' buoyancy and is therefore an operational descriptor as well.

d. Mixed Layer Sound Velocity (SV)

Mixed Layer Sound Velocity is defined as the mean sound velocity above the MLD.

e. Gamma at the Thermocline

With the assumption that the thermocline will have the maximum magnitude of gamma in the profile, the gamma with the greatest absolute value defines the thermocline. As above, the standard deviation of the SV above or below the layer, and a consistently large gamma for the next few depth segments can be used for error checking.

f. Deep Sound Channel (DSC) Axis

The Deep Sound Channel Axis is defined as the depth at which gamma is zero (inflection point) or where sound velocity is at its absolute minimum. For the case in which there is a secondary sound channel, the inflection point with the minimum sound velocity is the axis of the primary sound channel and any other inflection point defines the axis a secondary sound channel.

g. Deep Sound Channel Sound Velocity

Deep Sound Channel Sound Velocity is defined as the minimum SV in the profile. DSC SV is also used to calculate the Deep Sound Channel Strength.

h. Sound Velocity Difference

For deep water, with a mixed layer, Sound Velocity Difference is the difference between the sound velocity in the mixed layer and the DSC SV. For shallow water, Sound Velocity Difference defines the difference between the surface and bottom sound velocities. In the shallow water case it defines the strength of a surface half channel and in the deep water case it defines the strength of the shallow portion of the Deep Sound Channel. Although not a commonly used parameter, Sound Velocity Difference was developed in part to define the Deep Sound Channel Strength and was then seen to be a valid descriptor in itself for both deep and shallow water cases.

i. Deep Sound Channel Strength

Taking the SV at the bottom and subtracting the DSC SV, then comparing this difference to the Sound Velocity Difference, the Deep Sound Channel Strength is defined as the lesser of the two. In other words, the Deep Sound Channel Strength is the maximum SV change that a given sound ray would be subjected to in the DSC. For deep water, where the SV at the bottom is greater than the MLD SV, the DSC Strength is the Sound Velocity Difference. In shallower water, where the SV at the bottom is less than the MLD SV, the DSC Strength is the difference between the SV at the bottom and the DSC SV (Urick, 1983, pp. 163-164). For a secondary sound channel, an additional set of similar descriptors is used to describe its strength. Sound channel strength defines the low frequency cutoff for the channel (Naval Pacific Meteorology and Oceanography Detachment, Kaneohe Bay, Hawaii [NPMOC Kbay], 2005).

j. Gamma Deep

For unprocessed data, the profile may not extend to the bottom. In this case the Gamma Deep is defined as gamma at the deepest available depth. This is used to check whether the SVP profile extends into, or near, the pressure dominated regime in which gamma is 0.016 s^{-1} (Medwin and Clay, 1998, p. 4). If the profile does extend into this region, it can be extrapolated to the bottom. If it does not, then data from other profiles via optimum interpolation can be used to complete the profile. The other profiles can be additional unprocessed data or gridded data from climatology. This extrapolation was not used in the test case in Chapter V because the data used in the case study extends to the bottom. Follow on research that uses unprocessed data will need to be extrapolated.

k. Sound Velocity Deep

The deepest recorded SV is defined as the Sound Velocity Deep, and is used to extrapolate the SV at the bottom based on either the Gamma Deep or the pressure dominated gamma of 0.016 s^{-1}.

l. Bottom Depth

For unprocessed data, the bottom depth may be available in the header information of the SVP data or from a separate bathymetric database. For GDEM data, the Bottom Depth is already integrated into the profile.

m. Sound Velocity at the Bottom

If the deepest recorded SV is near the bottom depth (for example, within 10%) then the SV at the Bottom is a linear extrapolation to the bottom using Gamma Deep. If the Gamma Deep is near the pressure dominated gamma, then the Sound Velocity at the Bottom is again the linear extrapolation of the SV Deep to the bottom. If the Gamma Deep is not near 0.016 s^{-1} or the deepest recorded depth is not near the bottom, then there is no way to calculate the SV at the Bottom. In this case, other data can be used to extend the profile as described above or the profile can be used for shallow parameters only.

n. Sound Velocity Excess

Sound Velocity Excess is the difference between the SV at the bottom and the MLD SV and is a parameter used to determine if a Convergence Zone (CZ) propagation path is possible. In order for a CZ to occur the SV Excess must be greater than approximately 5.9 m/s. This represents about 0.4 percent of the mean SV. The presence of a CZ propagation path is usually defined in the U.S. Navy by a depth excess of at least 200 fm vice SV Excess (Bauer and Howlett, 1995, p. 180). This is based on the pressure dominated gamma in the deep ocean. A depth excess of 200 fm (365.8 m) with a 0.016 s^{-1} gamma gives 5.9 m/s SV Excess. Other definitions of depth excess use a total water depth versus surface temperature comparison which also equates to approximately 6.0 m/s SV Excess (Urick, 1983, p. 166).

Even though it is not normally used as a descriptor, negative SV Excess also describes a portion of the SVP. Negative SV Excess represents a difference in the strength of the shallow and deep halves of the DSC (Urick, 1983, pp 163-167). Negative SV Excess is allowed in the example process in Chapter V.

B. BOTTOM CHARACTERISTICS

Bottom interaction is a critical and well documented factor in sound propagation. In littoral waters, with simple SVPs like those used in the ESA, bottom characteristics are vital to sound path determination (Urick, 1983, p.281).

There are two basic types of bottom description: noun name descriptions like sand, rock, gravel and silt, and acoustic descriptions like sediment density and sound velocity in the sediment. The first type can be used to derive the second if there is data or a model that relates them. For the purposes of this project, any characteristic that accurately describes the bottom and can be associated with acoustic properties is a valid characteristic for comparison, even if the characteristic is not formulated in acoustic terms. For example, the bottom types in the NAVOCEANO MIW database are useful as well as LFBL sediment sound speeds.

The propagation of sound in a medium is characterized by the acoustic impedance. Acoustic impedance is determined by the density and sound velocity in the medium. In general, when sound interacts with the ocean bottom, the sound energy is partly reflected and partly transmitted into the sediment. The magnitude of the reflected and transmitted portion of the energy is determined by the acoustic impedance contrast at the water/sediment interface. Figure 4 displays the complexity of sound interaction with only two layers of bottom sediment. The top medium represents the ocean and the bottom two represent two thin layers of sediment. Each medium is characterized by its density ρ and its sound speed c. The *T* and *R* notations represent the different boundary interactions that each ray encounters: *T* for transmission and *R* for reflection.

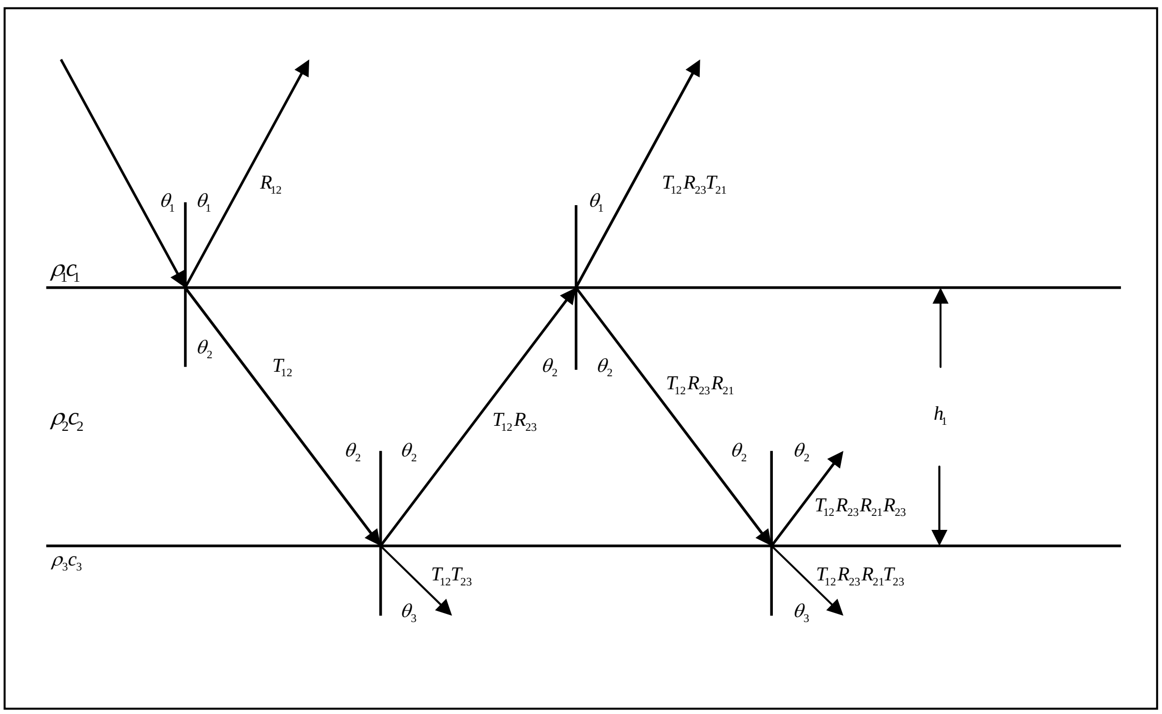

Figure 4. Example of reflection and transmission in a thin layer. [After Medwin and Clay, 1998, p. 47].

The factors that are used to describe sediment characteristics in the databases from Chapter II are described below.

1. Sediment Thickness

If a uniform sediment density is assumed, then a simple one layer sediment model can be constructed to represent sound interaction with the sediment. The NGDC Sediment Thickness is a simple model like this (NGDC, 2005d). For more complex models, like LFBL, the densities and thicknesses of several layers are considered. Sediment thickness is symbolized by h_1 in Figure 4.

2. Density and Sound Velocity in Sediment

A very accurate way to characterize the acoustic propagation of the sediment is with a multiple layer sediment model that describes the sound velocity, sound velocity gradient and density in all sediment layers. The LFBL database uses this approach (NAVOCEANO SID, 2001c).

3. Critical Angle

One acoustic method to determine the speed of sound in the sediment is through the empirical determination of the critical incident angle for the ocean sediment interface. A total reflection of sound energy occurs at the critical angle with negligible transmission. In Figure 4 the critical angle is the incident angle θ_1 for which the angle of refraction, θ_2, is 90 degrees. Given the speed of sound in the water, the measured critical angle and using Snell's Law with θ_2 equal to 90 degrees, the speed of sound in the sediment can be easily calculated:

$$\frac{c_1}{\sin\theta_1} = \frac{c_2}{\sin\theta_2}, \sin\theta_2 = \sin 90^\circ = 1$$

$$c_2 = \frac{c_1}{\sin\theta_1}$$

4. TWTT

Another measure of the sediment thickness and its acoustic properties is the Two Way Travel Time (TWTT) through the sediment layer. If a uniform sediment density underlain by a rigid boundary is assumed for a vertically propagating shear wave in the sediment, the TWTT describes the sediment thickness to the acoustic floor (Godin and Chapman, 1999, pp. 2372-2378).

5. Particle Size

Particle size distributions affect the porosity of the sediment, which is a factor in acoustic impedance. The size of the particles also affects scattering loss and what frequencies will experience this scattering. This is especially important for MIW and littoral USW where multiple bottom interactions make bottom loss a key element in propagation. Particle size can be used as a characteristic for comparison even though it does not completely describe the sediment because it is a physical descriptor for acoustics in the sediment.

C. BATHYMETRY AND BOTTOM SLOPE

While the bathymetry is an important input to the SVP, a range dependent propagation loss can also be affected by the bottom slope. From an operational perspective, the gradient of the depth contours is an important measure of upslope or downslope enhancement (NPMOC KBay, 2005). Bottom gradients can be another operational characteristic for comparison, but would have to be derived from the bathymetry data. Gridded data is well suited for this type of calculation because of its uniform distribution. For MIW applications the NGDC Coastal Relief Model could be used for detailed bottom slope comparisons.

D. VOLUME SCATTERING

Sound energy in the ocean is scattered by interactions with bodies and bubbles suspended in the water. Diffraction of sound energy also occurs in a process known as Raleigh scattering when the wavelength is much larger than the size of the particles in the water (Medwin and Clay, 1998, pp. 235-237, 271). The Volume Scattering Strength database describes the effect of the scattering on sound propagation. It catalogs scattering layer depth and strength seasonally and diurnally.

E. AMBIENT NOISE

Some of the sound sources that contribute to ambient noise like shipping noise, biologic noise, wave and surf noise, rain noise, noise from seismic activity and industrial noise have been cataloged. The databases that contain this ambient noise data include

SN, WRN, HITS and Surface Gridded Climatology. The ambient noise sources that have been cataloged can be categorized into three basic types: shipping noise, surface noise and biologic noise. SN is the only one of these databases that represents an attempt to describe the noise levels themselves and contains all three types of data. All the others are descriptive and require modeling to determine sound levels.

1. Shipping Noise

The HITS database is an attempt to model the number of ships transiting the ocean by area, month and ship type using historical data of recorded ship transits. As described in Chapter II, HITS data are valid characteristics for comparison. The SN database contains estimates of ambient noise contributions from HITS (NAVOCEANO SID, 2004, p. 16, 18).

2. Surface Noise

The sound produced by wind, rain and wave motion can be derived by modeling the sound produced by each of these weather related phenomenon. The WRN database, which describes noise levels for various wind spectra, is an example of this type of modeling. Other valid sources for surface related noise are climatological wind, rain, wave height and surf databases like NAVOCEANO's Surface Marine Gridded Climatology. Since this project can use physical descriptors as well as sound level estimates for ambient noise comparisons, both of these types of data are useful. The SN database includes derived sound levels from the Surface Marine Gridded Climatology database (NAVOCEANO SID, 2004, p18-20).

3. Biologic Noise

Often a large contribution to ambient noise, the research for this project has located only one data set that explicitly describes this type of noise. A portion of the WRN database contains historical whale provinces. This is a valid descriptor for whale noise and may be useful for exercise planning purposes where marine mammal impact analysis is required. The SN database contains estimates of ambient noise contributions from biologics (NAVOCEANO SID, 2004, p. 18-19).

IV. POSSIBLE BASIC METHODOLOGIES FOR DATA ANALYSIS

An important distinction must to be made about methods of characterizing an environment. Descriptive physical data can be used to model the propagation of sound in the ocean. This model's output can then be used as a basis for comparison of different ocean areas. For example, SVP data can be input into a modeling program like PCIMAT and the output propagation loss curves for different areas compared. Since the model outputs are dependant on the descriptive physical data, the data by itself is sufficient to describe the physical properties of the ocean which determine acoustic propagation. Modeling the sound propagation is not required. Any description of the physical environment in the ocean can be used for comparison, even if it is not cataloged in acoustic terms. For example, sediment grain size, which effects sediment acoustic impedance, can be used as a basis for comparison of sediment acoustic properties. Similarly, non-acoustic parameters, which affect other physical process, like radar propagation, can be used by themselves.

The purpose of this project is to produce a process for comparing ocean areas in operational terms. Although the data for a model is similar to the data used in this process, a computer model of the environment is not required. Because the comparison process was developed from the beginning to have an open architecture, there is no limit to the number of features that can be introduced into the environmental characterization. Unlike a model, when new data types are added the comparison process does not explicitly determine how physical processes are affected. For example, in an acoustic model, adding the LFBL database to the description of the bottom would represent a fundamental change in modeling the bottom interaction. In the comparison process, this new bottom data is simply another characteristic for comparison. The data provided must be sufficient for an accurate physical description even though physical processes are not modeled in the comparison.

A. COMPARISONS

Three comparison techniques were introduced in Chapter I: using weighting factors, using a decision tree and using fuzzy logic.

1. Weighting Factors

One approach to comparing parameters is to simply take the ratio between them to determine their similarity. For example, two MLDs can be compared by taking the lesser of the two and dividing it by the greater of the two. A MLD of 50 m is compared to a MLD of 25 m by taking 25/50 = 0.5, i.e. a 50% similarity. When considering a set of parameters, the ratio of each is taken, the ratios summed and the total normalized by the number of parameters. Two sets of characteristic that are similar will have a total correlation close to 1.0. For example, a SVP with MLD of 25 m, DSC Axis at 1000 m and Bottom Depth of 2300 m, when compared to a SVP with MLD of 50 m, DSC Axis at 700 m and Bottom Depth of 2500 m has a correlation of: $({}^{25}\!/_{50} + {}^{700}\!/_{1000} + {}^{2300}\!/_{2500}) \times {}^{1}\!/_{3} = 0.706$, i.e. a 70.6% similarity. When weighting a small series of simple parameters, this comparison can produce very similar sets with strong correlation. One drawback to this type of comparison is that it can produce similar scores for two sets that are marginally similar in many ways or are very similar in only a few ways, but are very dissimilar in a critical way. The more factors used for comparison, the less likely the correlations will be meaningful because variations in any one parameter will have less affect on the total correlation. The comparison becomes more and more qualitative and less quantitative.

Another more complicated comparison method consists of assigning weights to the various parameters depending on their relative importance in the total correlation. The parameter ratios are multiplied by the weighting factors, the weighted ratios summed and the total normalized by the sum of the weights. Continuing the example above, assigning arbitrary weights of 1.0 for MLD, 0.8 for DSC Axis and 0.5 for Bottom Depth gives a weighted correlation of:

$$((1.0 \times {}^{25}\!/_{50}) + (0.8 \times {}^{700}\!/_{1000}) + (0.5 \times {}^{2300}\!/_{2500})) \times {}^{1}\!/_{(1.0+0.8+0.5)} = 0.660$$

This represents a weighted similarity of 66%. A correlation close to 1.0 gives a good mathematical match and a good physical match if the weights were determined realistically. This method is better than the un-weighted method because the weighting mitigates the drawback described above. Sets with highly weighted parameters that are dissimilar will have low total correlations.

One significant advantage of the weighting factor approach is that it is very open. Adding a new parameter for comparison only requires finding new data and determining the weight to assign the parameter.

2. Decision Tree

Another basic method of comparison is to use a series of heuristic rules to produce a dichotomous grouping of similar sets, i.e. a decision tree. A heuristic rule is a simple conditional logic statement that is used to separate sets, for example:

- If the MLD is less than 25 m, then assign the SVP to the Shallow MLD category.
- If gamma is always negative below the MLD, then assign the SVP to the No DSC category.

The decision tree method can produce similar sets. With more complex descriptions, more rules are needed and the tree becomes larger. In contrast to the weighting factor method, the decision tree is very specific to the process it describes. Adding data types can be very complex because adding data parameters requires new rules and a single parameter may require many rules.

A combination of weighting factors and heuristic rules is another method of comparison. A series of simple logic rules is used to narrow the field of choices and then weighting factors are used to determine a best correlation within the smaller dichotomous sets. The ESA and the example process in Chapter V use a similar combined approach utilizing fuzzy logic concepts (Miyamoto, 1999).

3. Fuzzy Logic

Fuzzy logic is a relatively new mathematical discipline within which an attempt is made to formalize a “common sense” problem solving approach using a series of simple logical statements. At its foundation is the concept that the real world is not black and white. The binary or bivalent descriptions of black and white are replaced by multi-valued or multivalent descriptions that convey many values of grayness (Kosko, 1993, pp. 4-17). Four basic concepts of fuzzy logic are outlined below: fuzzyness, fuzzy set membership, fuzzy entropy and heuristic logic.

a. Fuzzyness

The central concept of fuzzy logic is that the real world is accurately described in terms of "grey-ness" and not in black and white terms. Using a USW example, from a fuzzy perspective the entire ocean is to some degree both deep and shallow. This is in contrast to a binary perspective, in which some of the ocean is deep and the rest is shallow. In the binary perspective, there must be a definite depth at which the ocean changes from deep to shallow. The black line in Figure 5 represents this marked transition, with shallow defined as water at less than or equal to 100 fathoms and deep as water at greater than 100 fathoms. The red and blue lines on Figure 5 represent the fuzzy perspective, in which all water has both shallow-ness and deep-ness. To what degree water with a given bottom depth is deep or shallow is defined by its fuzzy membership (Kosko, 1993, pp. 18-43).

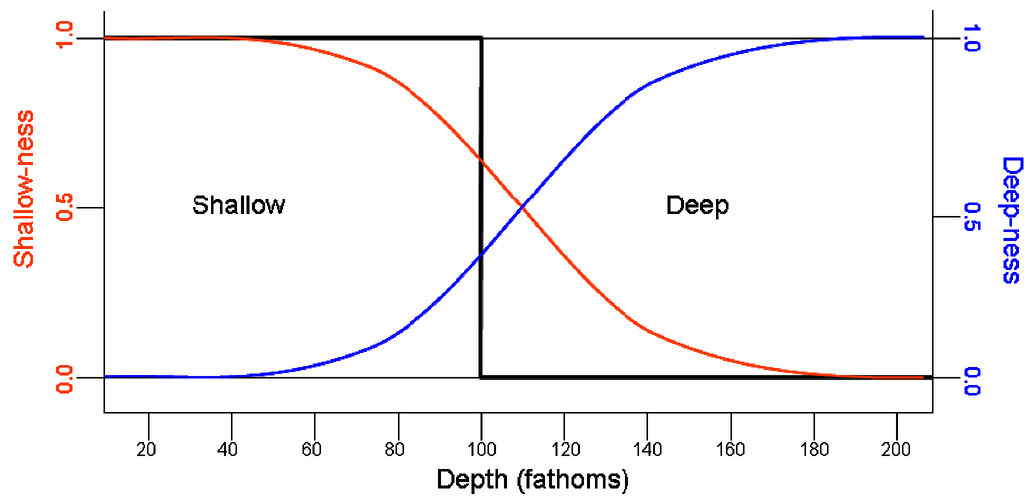

Figure 5. Example of Fuzzy Set Membership for Shallow-ness and Deep-ness. [After Kosko, 1993, p. 136].

b. Fuzzy Set Membership

Fuzzy sets are a way of describing the degree of grayness in the real world. Taking the red and blue lines in Figure 5 as example fuzzy set membership curves: water at more than 200 fathoms has 0% shallow fuzzy set membership and 100% deep fuzzy set membership, water at 40 fathoms has 100% shallow fuzzy set membership and 0% deep fuzzy set membership, and water in between has some fraction of both shallow and deep fuzzy set membership. For two different ocean depths (e.g. one at 80 fathoms and one at 120 fathoms) they have shallow-ness of 80% and 35% and deep-ness of 20% and 55%, respectively. The 80 fathom point has a fuzzy set membership of (0.8, 0.2) and the 120 fathom point has a fuzzy set membership of (0.35, 0.55). The fuzzy sets membership distribution is defined by the shape of the membership curve. The same depths in the example above would have different fuzzy set membership if the membership curves were changed.

The ESA and the example process in Chapter V use a percentile method to determine the fuzzy set membership. The cumulative distribution function for the actual distribution of the data in the sample space is used for fuzzy set membership determination.

c. Fuzzy Entropy

Fuzzy Entropy defines the amount of uncertainty in a system. When a set is fuzzy, its elements are contained in it only to a degree and this degree is uncertain. So the degree to which an element is contained in a fuzzy set is defined by the uncertainty and therefore the entropy. The degree to which two fuzzy sets intersect is also defined by an uncertainty and therefore an entropy. Fuzzy entropy between two fuzzy sets represents how much one fuzzy set is contained in another. The fuzzy entropy theorem states the fuzzy entropy of two sets is the ratio of their counted intersection and their counted union (Kosko, 1993, p. 133). Mathematically, this reduces to the ratio of the sum of the minimum set membership and the sum of the maximum set membership (Miyamoto, 1999). In the depth example above, the minimum shallow set membership is 0.35 and the minimum deep set membership is 0.2 (0.35, 0.2). The maximum shallow set membership is 0.8 and the maximum deep set membership is 0.55 (0.8, 0.55). By the fuzzy entropy theorem the fuzzy entropy is defined as: (0.35 + 0.2)/(0.8 + 0.55) = 0.41, i.e. a 41% similarity in bottom depth. The fuzzy entropy is also dependent on the shape of the fuzzy membership curves and represents a robust method of comparison for statistically distributed parameters.

d. Heuristic Rules

Another concept used in fuzzy logic is the use of simple if-then statements to define a process. Fuzzy heuristic rules are often applied to control systems like thermostats and industrial manufacturing processes. These heuristic rules are similar to the decision tree described in Section 2 above. Fuzzy logic methods allow the application of both weighting factors and heuristic logic. Examples of fuzzy heuristic rules are (Kosko, 1993, p. 163):

- If it is hot, then turn the air conditioner to high speed.
- If it is warm, then turn the air conditioner to medium speed.
- If it is cold, then turn off the air conditioner.

4. Complex Data Comparison

SVPs can be directly compared using a method like the least squares method, which consists of a point for point comparison. While this provides the most accurate mathematical match, it may not provide a physically significant match for two SVPs that have similar propagation properties. For example, two identical SVPs offset by 10 m/s will have no common points and therefore a low least squares fit, but will be operationally almost identical. There are ways to correct for this type of bias error, like de-meaning or de-trending the data. SVPs with similar acoustic propagation properties do not always have exactly the same shape and certain characteristics of SVPs have more effect on operational acoustics than others. Gamma in the deep ocean, for example, does not affect operations as much as gamma in the thermocline. Simple mathematical comparisons, like the least squares method, do not allow for individual characteristic descriptions of SVPs or have the flexibility to adjust the relative significance of characteristics of different parts of a SVP.

The process of determining important SVP parameters as outlined in Chapter III is an attempt to simplify the process of comparison while providing a set of operationally significant descriptive characteristics that can be weighted in terms of their relative effect on operations. The process also has the advantage of minimizing the amount of data that needs to be maintained in memory for comparison and therefore limits the computer capacity required. The development of a parameterization of SVPs vice the use of simple mathematical comparison methods allows for the incorporation of weighting factors which provide a more quantitative *operational* comparison.

B. UNPROCESSED VERSUS GRIDDED DATA

The lower vertical, horizontal and temporal resolution of gridded data must be weighed against the uneven distribution and potential lack of unprocessed data. Since most climatological data is a gridded monthly average, features that have high temporal variability will require unprocessed data to accurately characterize the environment. Based on a review of daily MODAS fields, MLD and other shallow SVP parameters may be better characterized on a time scale of weeks, not months.

Unprocessed data should be evaluated for use in describing vertically complex features like SVP, where temporally varying elements, like MLD, are not well interpolated in the gridded data. The MLD and thermohaline gradient are “averaged out” of these fields because the MLD is interpolated to one of the standard depths and averaged over a large area and time. The spatial and temporal averaging also tends to make the MLD and other shallow SVP elements less representative of possible extremes. These represent changes in tactically significant acoustic parameters like cutoff frequency in the surface duct or deep sound channel. The degree of temporal variation of a parameter, like MLD, may be useful as a descriptive characteristic in itself. The temporal variability of MLD would then become another physical descriptor for comparison.

GDEM and MODAS use the set of standard depths in Table 4. With only five possible depths for a MLD less than 100 m, the possible thermohaline gradients in OAML gridded data are dependant on the vertical resolution. A SVP that changed 1 m/s between 25 and 30 m has a gradient of 0.2 s^{-1}. The standard depth profile shows the same change in sound speed over 10 m or 0.1 s^{-1}, which is half the actual gradient.

Depth	**Level**	**Depth**	**Level**	**Depth**	**Level**
0	1	300	12	1400	23
10	2	400	13	1500	24
20	3	500	14	1750	25
30	4	600	15	2000	26
50	5	700	16	2500	27
75	6	800	17	3000	28
100	7	900	18	3500	29
125	8	1000	19	4000	30
150	9	1100	20	4500	31
200	10	1200	21	5000	32
250	11	1300	22	5500	33

Table 4. OAML Standard Depths. [From NAVOCEANO, 2005c]

For features that have no temporal variability, like bathymetry, the optimized gridded data is accurate and easier to manipulate than unprocessed data. Because databases like ETOPO2 were developed specifically for ocean modeling, the use of satellite derived sea floor elevation like ETOPO2 is adequate for area comparison. The exception is the shallow water environment for MIW applications, for which more detailed hydrographic products may be needed.

Unless all the data used for comparison is gridded at the same points, some method is required to interpolate the data. In the process example in Chapter V, the GDEM data is at 30 sec resolution and the NODC Sediment Thickness data is at 5 sec resolution. The average sediment thickness within each 30 sec rectangle is used to define the sediment thickness at the GDEM data points. When unprocessed data is used it must also be also be interpolated. The method of interpolating unprocessed data is a subject for follow on research.

C. AREA DETERMINATION

In the past there have been few, but relatively well defined, candidate areas used for comparison. The ESA study included only 29 pre-selected areas for which the majority of the data required was available (Miyamoto, 1999). In contrast, this project involves tens of thousands of source locations and must be open enough to allow processing of data for the entire globe. Some data may not be available for the target areas overseas at the same resolution as the data in U.S. waters. The NGDC Coastal Relief Model, for example, provides high resolution bathymetry data useful for MIW characterization but only has coverage for the continental shelf off the coast of the U.S.

With gridded data types, ocean characteristics are defined by a representative value for areas at the resolution of the database. For example, the GDEM database is at 30 sec resolution and each SVP profile represents an optimal interpolation of all the source profiles in the 30 sec by 30 sec rectangle centered on the gridded SVP.

Another way of defining ocean characteristics is to arbitrarily choose areas and examine the physical environment in these areas to determine representative values for descriptive characteristics. The ESA uses this approach. A pre-defined area may contain several very different environments and therefore single representative values may not accurately describe the area.

An approach was considered for this project that used the currently defined OPAREAS for comparison, characterizing an entire OPAREA with one data point. However the OPAREAS were found to be too large to be accurately characterized by a single set of descriptors. A gridded approach was therefore chosen, which has additional advantages. Because the grids are not limited to the OPAREAS, new areas in U.S. waters that correlate well to overseas areas can be found and considered for new OPAREAS. The gridded approach also allows expansion of the comparison process to a global scale. The comparison process can then be conducted in reverse, with OPAREAS used as the basis for comparison and overseas areas found that are similar to the OPAREAS. For example, the area in the Tongue of the Ocean at the Atlantic Undersea Test and Evaluation Center (AUTEC) could be compared to the global oceans and areas found that are similar to the AUTEC range. Even though unprocessed data will be used in future research because it will allow for better vertical and temporal resolution, defining the characteristics in a grid space instead of using predefined areas provides greater flexibility in the application of the comparison process.

The overseas areas that are the basis for comparison will most likely be defined by more than one grid and therefore more than one unique set of target descriptors. The example process in Chapter V uses two such distinct sets from two areas near each other.

If the comparison process is expanded to include gridded target areas, the comparison process will also determine the extent of the area for which the comparison is valid. Target area determination would involve examining the areas around a chosen target point to find where the environment changes from that target point and therefore where another target point is needed. The comparison process is then used not only as a tool for analog determination but also as a tool to define the extent of areas with similar characteristics. If the example process had been used in this way, an area in the East China Sea would have been identified that had similar characteristics to the single profile chosen for comparison.

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V. EXAMPLE COMPARISON PROCESS

The example process developed for this portion of the project is detailed below. As mentioned in Chapter II, the SVP database used is the Generalized Digital Environmental Model (GDEM) with the DBDBV and ETOPO2 derived bathymetry taken directly from GDEM. The NGDC Global Sediment Thickness is used to represent both bottom data and the addition of other data types to the process.

The process consists of seven basic segments: (1) parsing the source data to determine descriptive factors for the SVP, (2) consolidating and adding sediment thickness to the descriptive data, (3) parsing the target SVP data with sediment thickness added, (4) calculating the adjusted weighted total fuzzy entropy for each location and month, (5) displaying the data using the ArcMap program for comparison and evaluation, (6) verifying the process output by comparing the SVPs at several locations with high and low match scores, and (7) running the PCIMAT propagation loss model at the same locations.

A. PARSING THE SOURCE DATA

1. Importing the SVP into MATLAB

A set of SVPs was extracted from the GDEM database using the open source interface at https://128.160.23.42/gdemv/gdemv.html. Three source areas were identified and extracted: (1) the east coast of the United States, the Gulf of Mexico and the Caribbean, (2) the west coast of the United States and (3) the area around Hawaii. Each area required the download of 12 files, one for each month, for a total of 36 files. Each area has its own set of files for output which are combined in the fuzzy entropy calculation step described in Section D. The source areas are shown in Figure 6.

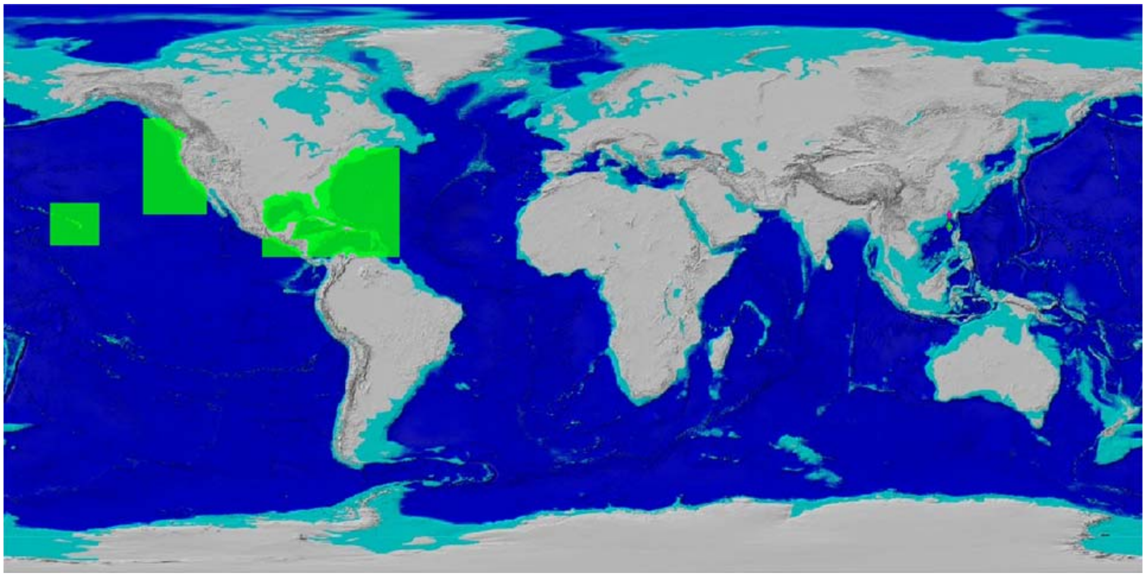

Figure 6. Source Areas (Green) and Target Areas (green and magenta diamonds near southwest Asia). [After ArcIMS Image Service (ArcIMS)].

2. Determining the Descriptive Parameters.

Because the gridded data from GDEM is consistently formatted and error checked, the process of SVP characteristic determination is simpler than that outlined in Chapter III. Each data file consists of thousands of individual SVPs separated by header information for each profile. A typical GDEM SVP, as extracted, is displayed in Table 5. Having the number of points in the profile listed in the header makes the extraction of the SVP very simple because it allows MATLAB to read only one SVP at a time and calculate data immediately. Column one is the depth in m, column two is the temperature in $^{\circ}C$ and column three is the salinity in PSU. Note that the sound velocity is already calculated in column 4 in m/s.

The data is read line by line into a matrix with the number of points in the profile used to determining when a SVP is complete. This is checked by verifying that the last depth is equal to the max depth in the header line.

```
Lat:   20.00 Lon:  -54.50 Valid Days:001-031
Points  in  profile:       31  Min  depth:      0  Max  depth:  5557
Version:OAML GDEMV Reader 1.2  Classification: PUBLIC DOMAIN
    0.00   25.56   36.59 1537.91
   10.00   25.56   36.59 1538.07
   20.00   25.56   36.58 1538.23
   30.00   25.56   36.59 1538.40
   50.00   25.55   36.66 1538.79
   75.00   25.43   36.82 1539.10
  100.00   24.74   36.95 1538.05
  125.00   23.13   37.00 1534.64
  150.00   21.60   36.99 1531.17
  200.00   20.17   36.79 1527.98
  250.00   18.81   36.50 1524.70
  300.00   17.45   36.33 1521.40
  400.00   14.79   36.00 1514.51
  500.00   12.48   35.66 1508.14
  600.00   10.47   35.39 1502.43
  700.00    8.75   35.20 1497.52
  800.00    7.41   35.05 1493.87
  900.00    6.44   34.96 1491.61
 1000.00    5.77   34.91 1490.52
 1100.00    5.33   34.90 1490.39
 1200.00    5.05   34.90 1490.92
 1300.00    4.86   34.91 1491.82
 1400.00    4.69   34.96 1492.87
 1500.00    4.54   34.99 1493.96
 1750.00    4.03   35.03 1496.11
 2000.00    3.59   35.04 1498.51
 2500.00    3.05   35.00 1504.69
 3000.00    2.75   34.93 1511.93
 4000.00    2.24   34.89 1527.16
 5000.00    2.01   34.84 1543.89
 5557.00    2.12   34.83 1554.36
```

Table 5. Example GDEM SVP data.

Descriptive parameters for the SVP are calculated in the MATLAB code as follows:

Latitude: Latitude is read directly from the header line.

Longitude: Longitude is also read directly from the header line.

Month: Month is determined by dividing the last number in the "Valid Days" field by 30 and rounding down. A 59 in the "Valid Days" field is used as a tag to assign February as the month.

Surface Temperature: The first temperature in the profile is assigned as the Surface Temperature.

Mixed Layer Depth: MLD is calculated using the NMLD method: the MLD is the shallowest depth at which the temperature differs by more than 0.8 $^{\circ}C$ from the temperature at 10 m. The 0.8 $^{\circ}C$ ΔT criteria was validated by accurate MLD determinations based on visual inspections of SVPs from the source and target areas.

Mixed Layer Temperature: Mixed Layer Temperature is calculated as the mean temperature above the MLD.

Mixed Layer Sound Velocity: Mixed Layer Sound Velocity is calculated as the mean SV above the MLD.

Gamma in the Thermocline: Gamma is the rate of change in sound velocity with depth. Gamma is calculated by taking the gradient of the SVP matrix and dividing the sound velocity differences by the depth differences element by element giving $^{\Delta SV}\!/_{\Delta Depth}$ for each profile segment. The gamma in the profile with the maximum absolute value is assigned to Gamma in the Thermocline.

Deep Sound Channel Depth: The depth of the minimum SV in the profile is assigned to DSC Depth.

Deep Sound Channel Sound Velocity: The minimum SV in the profile is assigned to DSC SV.

Sound Velocity Difference. Sound Velocity Difference is the difference between the Mixed layer SV and the DSC SV.

Deep Sound Channel Strength: DSC Strength is the minimum of the SV Difference, and the SV at the bottom minus the DSC SV.

Bottom Depth: The “Max depth” listed in the header is assigned as the Bottom Depth.

Bottom Sound Velocity: Because all GDEM data is extrapolated to the bottom, the SV at the last recorded depth is assigned to the Bottom Sound Velocity.

Sound Velocity Excess: Sound Velocity Excess is calculated by taking Bottom Sound Velocity minus MLD SV.

3. Binary Data Types

Four additional calculations are made to determine if the SVPs demonstrated shallow water characteristics. A fifth binary check is used in the fuzzy entropy calculations described in Section D to determine if a CZ propagation path is possible. A separate binary data type is not needed for CZ propagation determination because the SV Excess parameter carries this information.

a. Isovelocity

Isovelocity is defined as a SVP that has a standard deviation of less than 0.2 for the entire profile. The value of 0.2 was determined based on the successful identification of profiles with variation of less than 3 m/s. Sensitivity analysis to this standard deviation value should be a subject of follow on research. A value of 1 is assigned for isovelocity and 0 for variable velocity.

b. Upward Refracting

If a SVP has a gamma value greater than zero for the entire profile, it is defined as upward refracting. A value of 1 is assigned for upward refracting and 0 for not upward refracting.

c. Downward Refracting

If a SVP has a gamma value less than zero for the entire profile, it is defined as downward refracting. A value of 1 is assigned for downward refracting and 0 for not downward refracting

d. No Deep Sound Channel

Once the mixed layer depth is determined, if the gamma below the MLD is always negative, the profile is defined as having no deep sound channel. A value of 1 is assigned for no deep sound channel and 0 for having a deep sound channel.

If a profile exhibited any of these four features, the deep sound channel parameters are set to “not a number” (NaN). NaN is a MATLAB programming feature that allows undefined numerical values to be carried within numerical data. Isovelocity profiles have the MLD set to the bottom depth and the mixed layer parameters set to define the entire profile.

The output of the source profile parsing program is a set of descriptive parameters for each SVP. A total of 83,160 profiles were parsed representing 6,930 locations for 12 months each: 52,080 in the East Coast section, 21,048 in the West Coast section and 10,032 in the Hawaii section.

B. ADDING SEDIMENT THICKNESS

Once the source areas are determined, the NGDC sediment thickness database is parsed to get the sediment thickness data for the source locations in the GDEM data. The entire sediment thickness database is available in ASCII format as xyz data at http://www.ngdc.noaa.gov/mgg/sedthick/sedthick.html.

The NGDC database is read line by line and checked to find the data points which are in one of the predetermined source areas of interest, which are then written to an output file for that area.

The sediment thickness data set for each source area is loaded and then the parsed SVP descriptive data for that area is read line by line. The sediment thickness data is checked to identify all the data within 15 sec of the SVP data point. The GDEM data is at 30 sec resolution and the NGDC sediment thickness is at 5 sec resolution. The sediment thickness data within 15 sec of each SVP data point are averaged and taken as the sediment thickness for that 30 sec by 30 sec area. Except for points on the edge of the source areas, each GDEM data point has 36 corresponding NGDC data points. A new descriptive line of data, including the sediment thickness, is written to an output file. This file contains all 20 descriptive parameters for each SVP: three for location and time, four binaries for heuristic logic use and 13 for describing the physical characteristics of the profile. The parameters are listed below:

- Latitude
- Longitude
- Month
- Isovelocity
- Upward Refracting
- Downward Refracting
- No Deep Sound Channel
- Surface Temperature
- Bottom Sound Velocity
- Sound Velocity Difference
- Mixed Layer Depth
- Mixed Layer Temperature
- Mixed Layer Sound Velocity
- Maximum Gamma
- Deep Sound Channel Sound Velocity
- Deep Sound Channel Depth
- Deep Sound Channel Strength
- Sound Velocity Excess
- Bottom Depth
- Sediment Thickness

Code is also written to add already extracted data from the NGDC sediment thickness database to the SVP descriptive data. Both this code and the code described above establish the method to add additional types of data to the descriptive database.

C. PARSING THE TARGET DATA

A point extraction from the GDEM database was used for two target areas: A "deep water area" in the East China Sea between Luzon and the continental shelf in January, at Latitude 20 degrees North and Longitude 119 degrees East, and a "shallow water area" in the southern Taiwan Strait in September, at Latitude 23.5 degrees North and Longitude 119 degrees East. These locations were arbitrarily determined based on the need to test deep and shallow water areas that were outside the predetermined source areas. Other target areas can be chosen and input into the process at this point. The target areas are displayed in Figure 7.

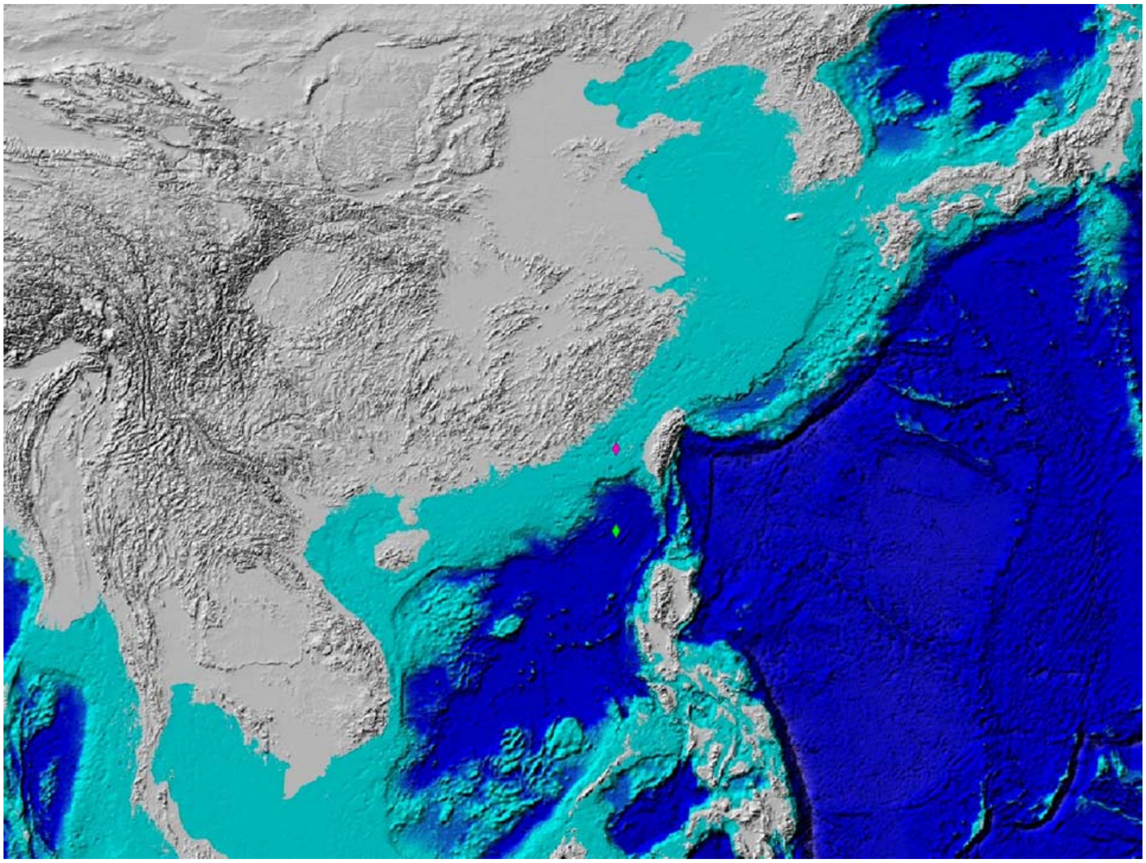

Figure 7. Target Areas. Deep (green) and Shallow (magenta). [After ArcIMS].

Each target SVP is parsed exactly like the source data and the sediment thickness manually extracted from the NGDC sediment thickness data. Although code is written to do this automatically by reading the full NGDC database line by line, the manual method is less time intensive.

D. CALCULATING ADJUSTED WEIGHTED FUZZY ENTROPY

All the descriptive data, starting with one target area, are combined into one large matrix. Each row contains the 20 descriptive parameters listed in Section B for a data point defined by its location and month. Each column contains all the data for a specific parameter in the sample space defined by the three source areas plus the single target data point.

A fuzzy entropy matrix is developed by comparing each one of the 13 numerical parameters for individual data points with the target parameters. The location and month columns from the descriptive data matrix are copied and the fuzzy entropies added column by column as detailed below.

For fuzzy set determination, each parameter is ranked by percentile within the entire data space. For example, the bottom depth is ranked from shallow to deep, with each percentile (1-100) represented by a depth value based on the distribution of depths within the three source areas.

Three fuzzy sets are established for high, medium and low percentiles. The membership curves in Figure 8 are derived from the actual depth distribution in the source areas. Each individual data point depth is given a percentile value interpolated within the percentile rank and then assigned membership in the three fuzzy sets based on that percentile rank. Membership in the high, medium and low fuzzy sets is defined by how close the individual depth percentiles are to the 100th, 50th and 0th percentile respectively.

The fuzzy entropy is calculated for each data point depth using the fuzzy set membership for the individual data point and the target data point as displayed in Figure 9. Following the Fuzzy Entropy Theorem, the sum of the minimum set membership is divided by the sum of the maximum set membership to give the fuzzy entropy. In the example, a bottom depth at 30th Percentile (e.g. South China Sea) has: 0% High, 59% Medium and 50% Low Fuzzy Set membership, (0.0, 0.59, 0.5) and bottom depth at 70th Percentile (e.g. Virginia Capes) has: 29% High, 67% Medium and 0% Low Fuzzy Set membership, (0.29, 0.67, 0.0). Between these two depths, the minimum set membership is (0.0, 0.59, 0.0) and the maximum set membership is (0.29, 0.67, 0.5), which gives a fuzzy entropy of: $\frac{0.0+0.59+0.0}{0.29+0.67+0.5}=\frac{0.59}{1.46}=0.404$. This represents a 40.4% similarity (Kosko, 1993, p. 133 and Koiman, 1999). The data point depths are represented in the fuzzy entropy matrix by a column of fuzzy entropies between 0 and 1 which correspond to their similarity to the target depth. Each numerical descriptive parameter's fuzzy entropy is calculated in the same way and added to the fuzzy entropy matrix.

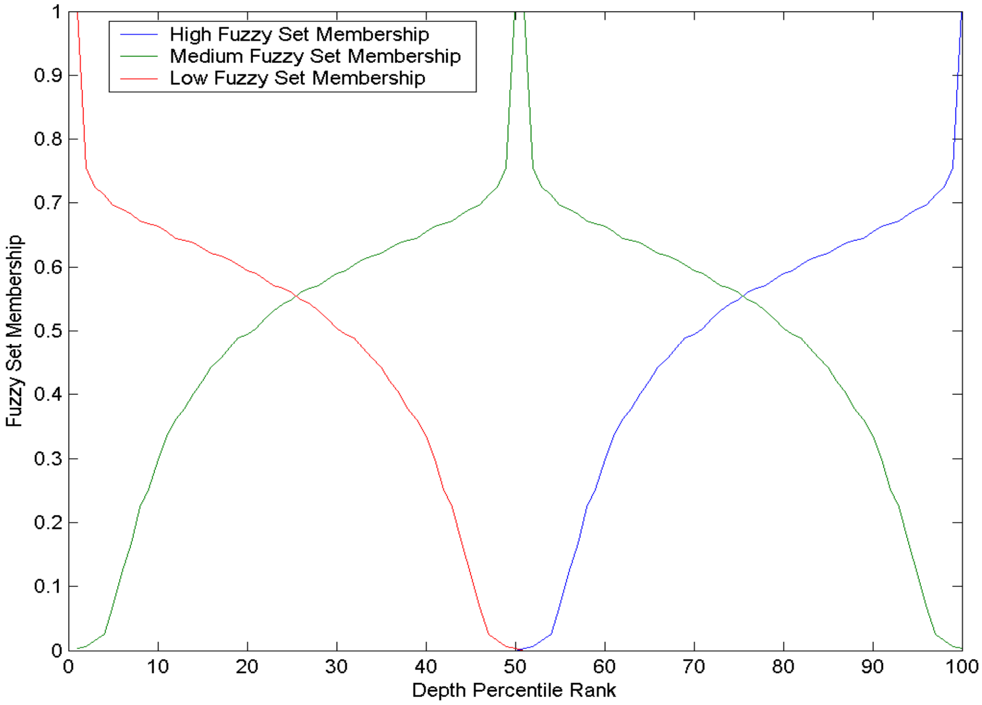

Figure 8. Fuzzy Set Membership Curve Example.

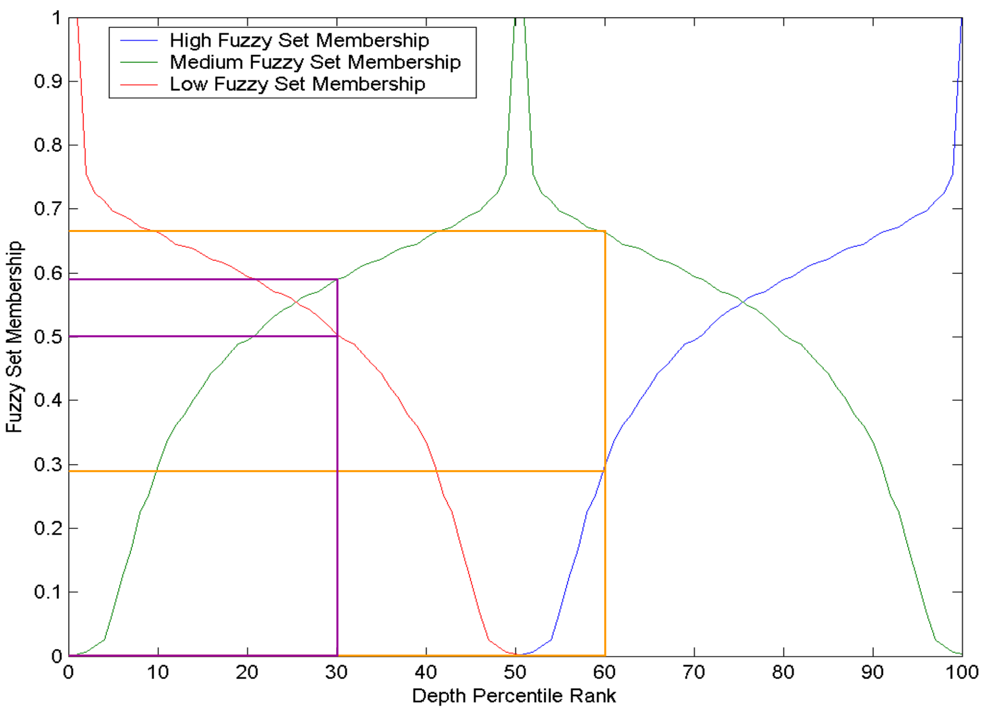

Figure 9. Fuzzy Entropy Calculation Example.

The fuzzy entropy matrix now consists of a set of three position and time parameters and 13 descriptive physical parameter entropies. A set of weights is assigned to each numerical parameter. For this case study a set of hypothetical weights based on a reasonable estimation of the importance of the physical parameters for a "Deep Water USW" mission is used. A sensitivity analysis of these weights to determine a more accurate set is a suggested topic of further research. The weights used are listed below:

- 0.25 for Surface Temperature
- 0.25 for Sound Velocity at the Bottom
- 1.0 for Sound Velocity Difference
- 1.0 for Mixed Layer Depth
- 0.5 for Mixed Layer Temperature
- 0.75 for Mixed Layer Sound Velocity
- 1.0 for Thermocline Gradient
- 0.75 for Deep Sound Channel Sound Velocity
- 1.0 for Deep Sound Channel Depth
- 1.0 for Deep Sound Channel Strength
- 0.75 for Sound Velocity Excess
- 0.5 for Bottom Depth
- 1.0 for Sediment Thickness

In general, the weight of individual parameters like surface temperature and sound velocity at the bottom are low, because they would tend to anchor the profile to a specific value. Weights of gradients and differences are higher because they describe the shape of the SVP. The sediment thickness is weighted high to ensure that it, as the only factor not based on the SVP, is adequately represented in the environmental comparison. Again, these are only a reasonable estimation of the importance of the various factors.

Since the weights above are based on "deep water USW," they need to be adjusted for special cases. As an example, two sets of heuristic rules are used to adjust the weights for shallow water using the four binary checks. Another set of rules is used to adjust weights for a deep water example using a sound velocity excess of 5.9 m/s as a binary for the existence of a convergence zone propagation path. These weight adjustments are based on a hypothetical estimation of the reasonable importance of the physical parameters in shallow water or for convergence zone propagation. The heuristic rules are applied to all the data based on the parameters of the target SVP. For the target SVP in the Taiwan Strait, the weights are adjusted as “Shallow”. The heuristic rule examples are listed below:

- If "Shallow" as indicated by any one of the four binaries then:
  - Set DSC weights to zero
  - Double the weight of the Bottom Parameters
  - Increase the weight of Mixed Layer Temperature and Mixed Layer Sound Velocity by 1.25
  - Increase the weight of Bottom Sound Velocity and Sound Velocity Difference by a factor of 1.5
- If Upward Reflecting:
  - Decrease Bottom Characteristic weights by 0.25
  - Increase Sound Velocity Difference weight by 1.5
  - Increase Surface Temperature weight by 1.25
- If SV Excess > 5.9 m/s (CZ propagation possible):
  - Double the weight of Sound Velocity Excess
  - Set Bottom Characteristic weights to zero

For shallow water, it is important to set deep sound channel weights to zero even though the values are already NaN because the total entropy is normalized by the sum of the weights.

After the weights are assigned and adjusted, the weight matrix is replicated to match the size of the entropy matrix and multiplied element by element. The set of weighted entropies for each location is then summed and normalized by the sum of the weights. The final MATLAB output is a set of total weighted fuzzy entropies by location and month. The total weighted fuzzy entropies represent the “match score” for each source location when compared to the target location. The process from the parsing of the target data through the total entropy calculation is repeated for each target area. In this case there are two output data sets, one for the deep water example and one for the shallow water example.

Because the fuzzy entropy calculations use the inherent distribution of each property within the sample space for fuzzy set membership, the process eliminates the need for statistical modeling of the data distribution. If this were not the case, an arbitrary distribution function would be applied to fuzzy set membership and the resulting fuzzy entropies would be less accurate. Some caution is required when determining the areas for comparison. Because the percentile ranking within the sample space is used for fuzzy set membership determination, changing the sample space will affect fuzzy set membership and therefore the fuzzy entropy. If the source areas in this example were expanded to the whole world, the total weighted entropies for the sample areas in the current limited regions would change to reflect different distributions of data within the sample space, leading to different fuzzy set membership, different fuzzy entropies and different match scores. Because the various parameter distributions would vary in different ways, the resulting match scores may show different relative values. The final results may be different. This can be mitigated by ensuring that the sample space is large enough that the distributions approach normal and that the source areas have parameter ranges that include the target parameters.

E. DATA DISPLAY

For the purpose of providing a consolidated display of match score data, the single maximum monthly total entropy value for each location and each month was output to a text file. Each location is represented by the weighted entropy for the month with the highest match score. In addition to this consolidated display, an example atlas of match scores, by month, for each target location is included in Appendix B and C.

The match score file is opened in Microsoft Excel, header information added (latitude, longitude, month and match) and then saved as a dBase 4 file. ArcMap does not recognize .xls or .txt files as valid formats for input and MATLAB cannot output .dbf or .xls files. The file size for these display files is limited by total number of rows allowed in an Excel spreadsheet: 65536 lines.

The .dbf file is loaded into ArcMap as “xyz” data and match score data displayed as color coded areas. Figures 12 through 18 display the color contoured match scores for the deep and shallow water target areas. The ArcIMS imaging service has an open source graphic contour map of the entire world that is used as a base layer for the example data display. The UNCLASSIFIED OPAREA overlays are from a set of shape files provided by the Naval Pacific Meteorology and Oceanography Center, San Diego, California.

1. Deep Water Example

The color contoured deep water match scores for the source areas are displayed in Figure 10. Red represents a low match (>20%) and light green represents a high match

(>80%). The very shallow areas on the continental shelf scored low, with deep water scoring in the 40-60% range and waters just off the continental shelf, off the East Coast and in the Gulf of Mexico, scoring the highest. The Hawaiian areas also scored in the 40-60% range. The same contours with the OPAREA outlines are displayed in Figure 11. An enlarged view of the region off the east coast with OPAREAS is in Figure 12. The highest match scores are in the southern Virginia Capes Operating Areas (VCOAS) and the Cherry Point Operating Areas (CPOAS). The highest single match score of 82.5% is in the CPOAS as indicated by the green diamond on Figure 16.

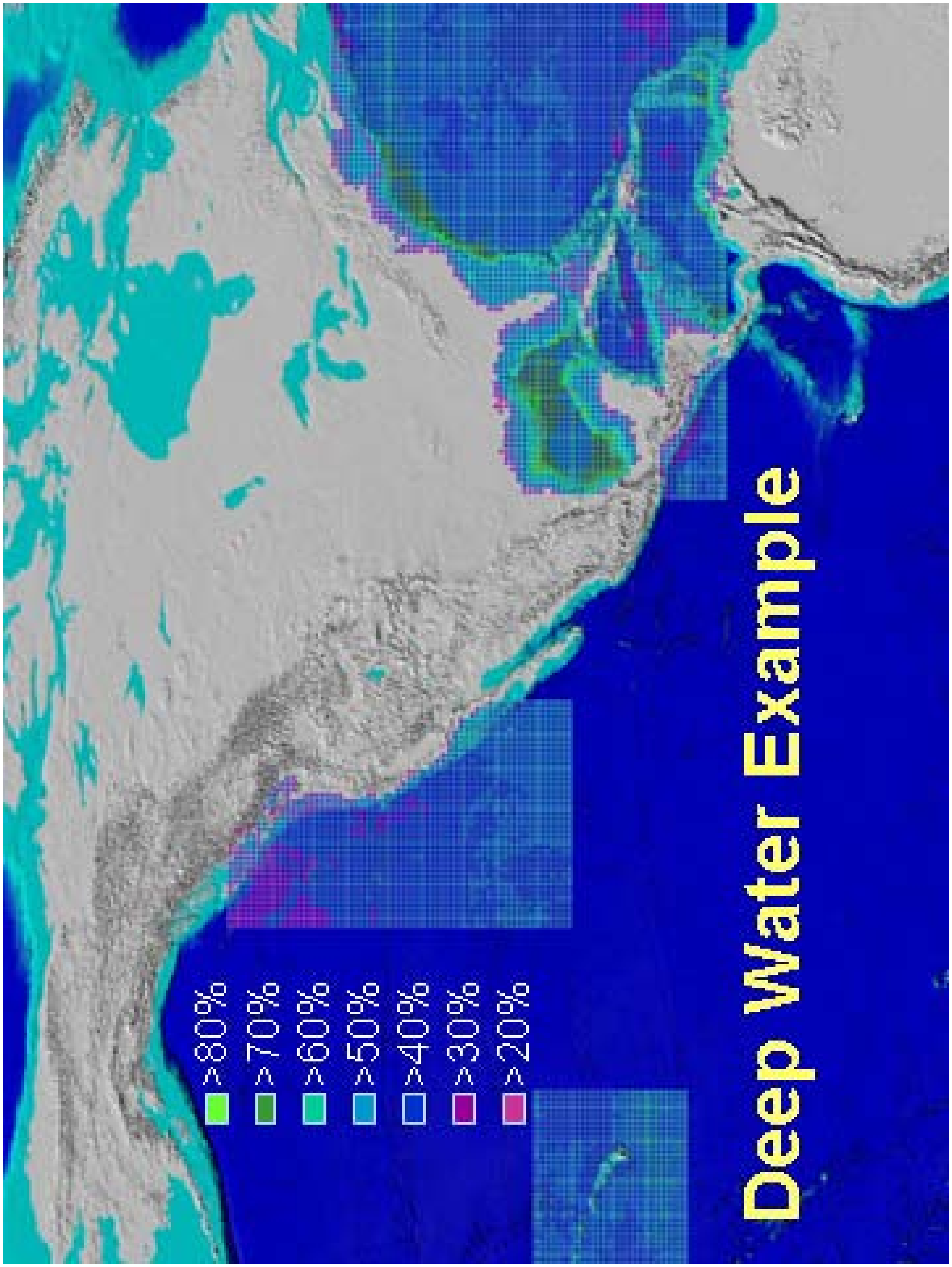

Figure 10. Deep Water Color Contoured Match Score. [After ArcIMS].

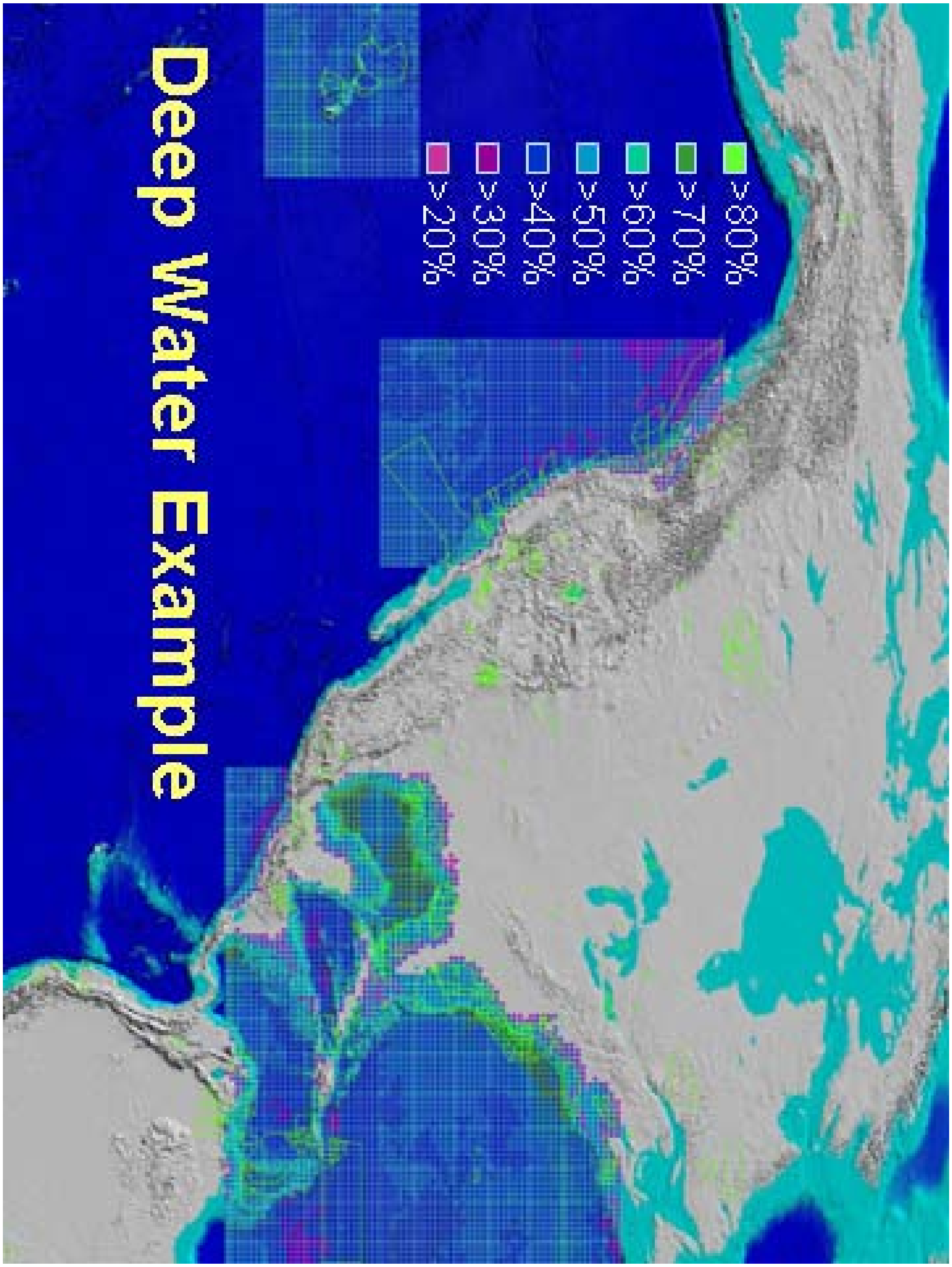

Figure 11. Deep Water Color Contoured Match Score with OPAREAS. [After ArcIMS and Naval Pacific Meteorology and Oceanography Center, San Diego (NPMOC SD), 2005].

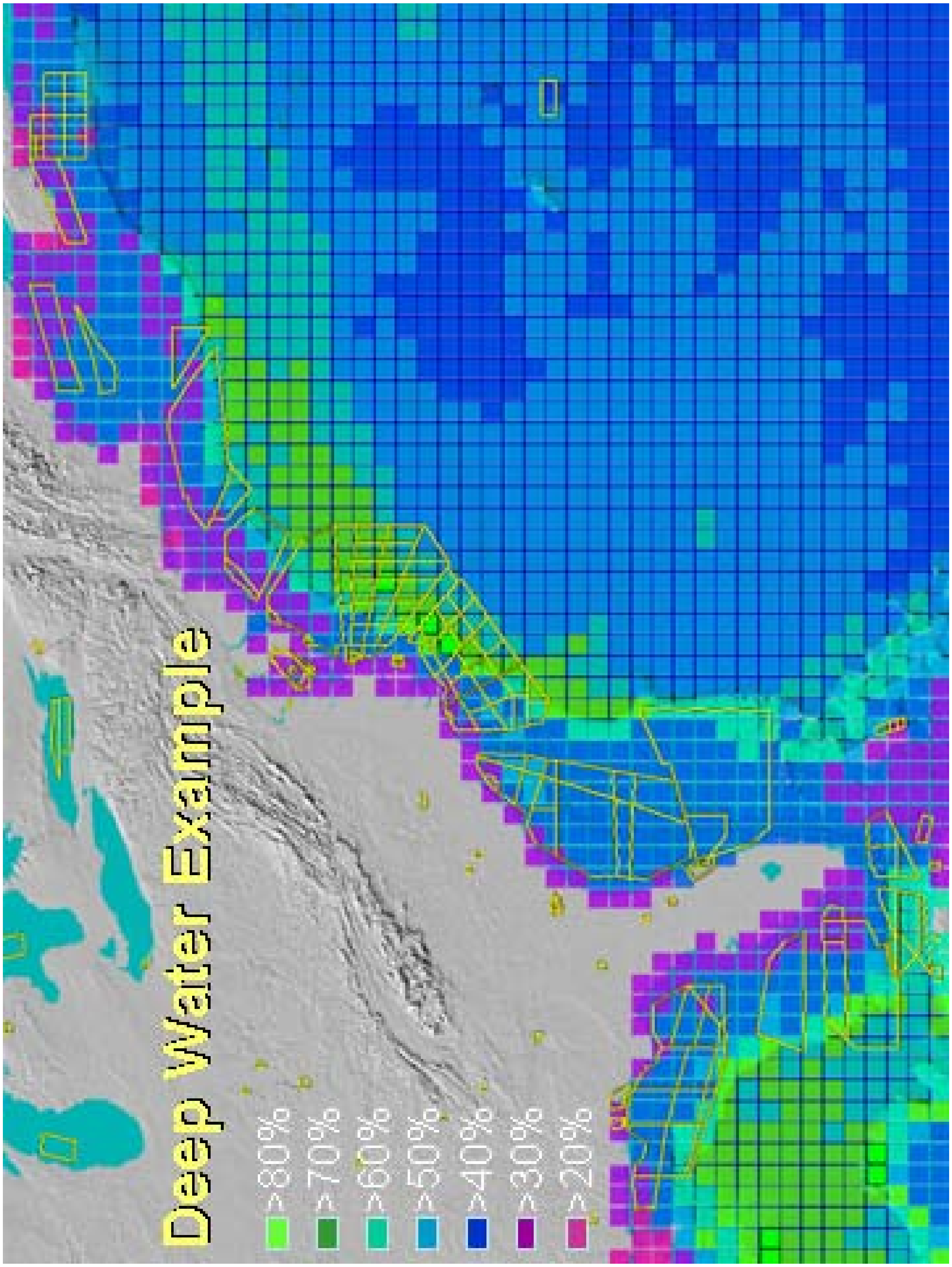

Figure 12. Deep Water Color Contoured Match Score with OPAREAS (Enlarged). [After ArcIMS and NPMOC SD, 2005].

2. Shallow Water Example

The color contoured shallow water match scores for the source areas are displayed in Figure 13. The same contours with the OPAREA outlines are displayed in Figure 14. The deep water areas, including all of Hawaii, scored in the 20-40% range and the shallow waters on the continental shelf, on both coasts, scored in the 60-80% range. The very shallow waters on the continental shelf in the Gulf of Mexico, the Caribbean and off the east coast all scored high, in the 70-90% range. The highest single score was 90.9% off the east coast of Nicaragua. An enlarged view of the region off the east coast with OPAREAS is in Figure 15. The highest scores are in the Jacksonville Operating Areas (JAXOAS) with a high score for the region of 86.2% as indicated by the magenta diamond on Figure 16.

Although the results shown are based on hypothetical weights, there are trends which provide first order validation of the process. For both examples, the best matches were on the eastern continental shelf, which correspond to the geography of the target locations. The target locations and high score source locations are also affected by western boundary currents (i.e., the Kuroshio and the Gulf Stream).

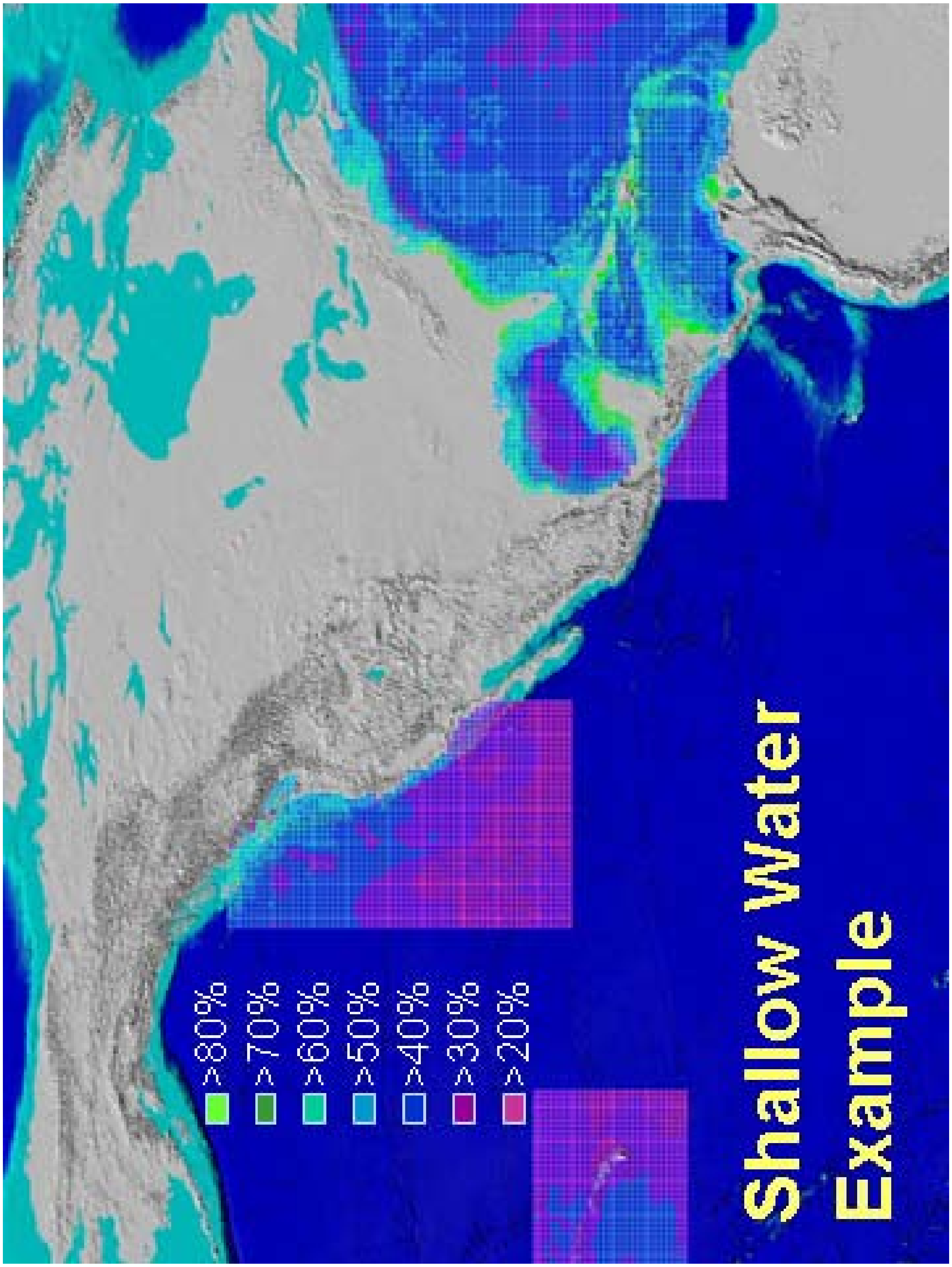

Figure 13. Shallow Water Color Contoured Match Score. [After ArcIMS].

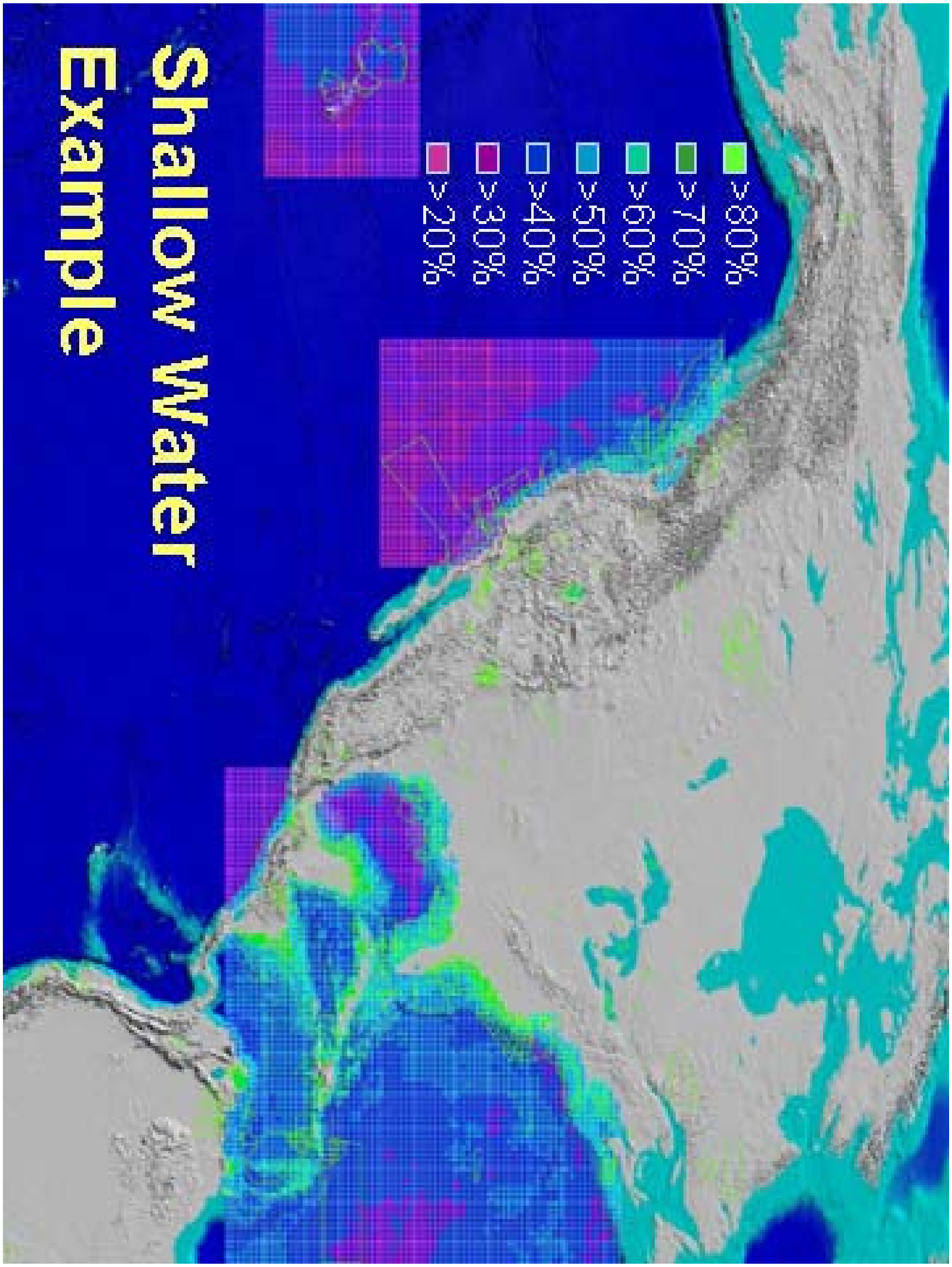

Figure 14. Shallow Water Color Contoured Match Score with OPAREAS. [After ArcIMS and NPMOC SD, 2005].

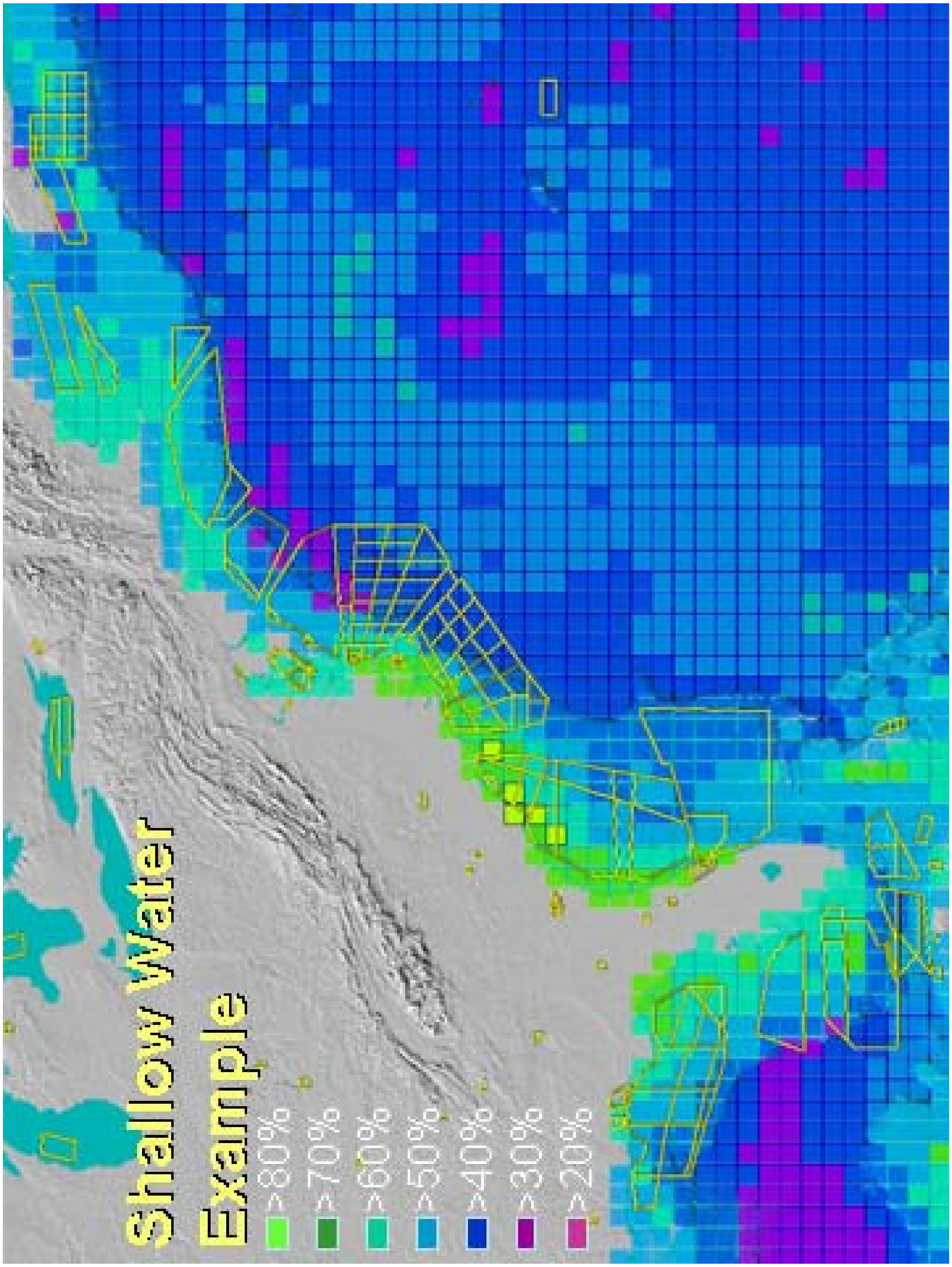

Figure 15. Shallow Water Color Contoured Match Score with OPAREAS (Enlarged). [After ArcIMS and NPMOC SD, 2005].

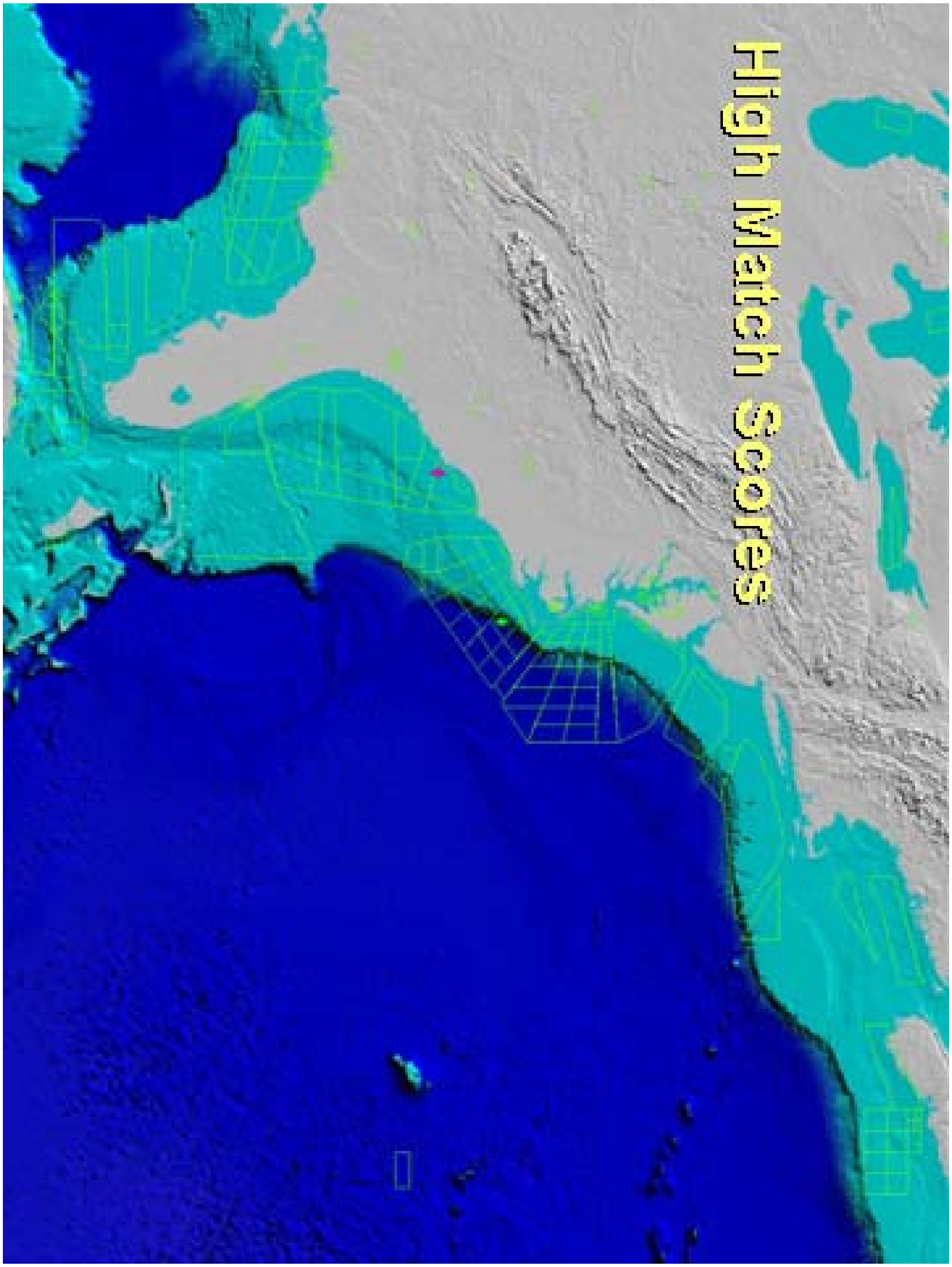

Figure 16. Maximum Match Scores within OPAREAS. Green deep and magenta shallow [After ArcIMS and NPMOC SD, 2005].

F. EXAMPLE SOUND VELOCITY PROFILE COMPARISONS

1. Highest Match Score Comparison

Figure 17 shows the temperature, salinity and sound velocity profiles for both the deep water target and the highest scoring source area (CPOAS). The temperature profiles show similar gradients and shape. The same is true of the salinity profile except for a bias in the upper profile. The SVP is similar, with similar MLD, DSC Axis, maximum SV gradient, SV difference and SV excess. A least squares fit would have been poor for these two profiles because there are no points in common and the shape of the upper half of the DSC is different. However, the two profiles exhibit similar operational characteristics and will be shown in Section G to have similar acoustic propagation losses.

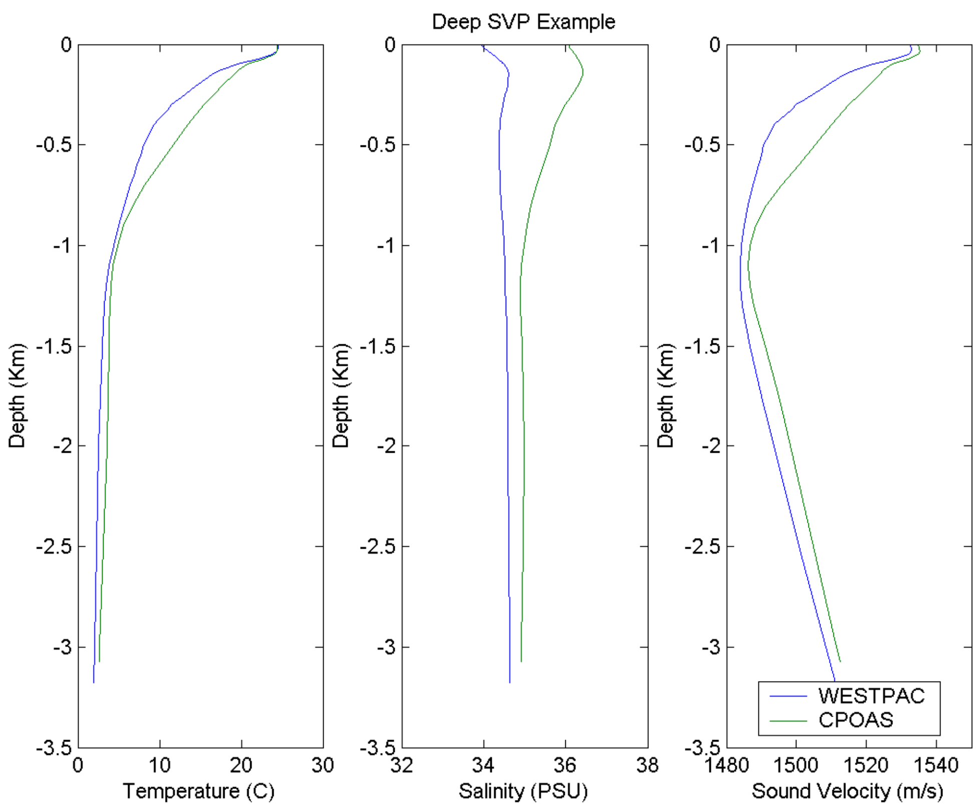

Figure 17. Highest Match Score Deep Water Profile Comparison.

Figure 18 shows the temperature, salinity and sound velocity profiles for both the shallow water target and the highest scoring source area (Nicaragua) with the same horizontal scale as Figure 17. Note the vertical scale change from km to m. At this scale the temperature and SVP profiles are very close with a similar slope to the salinity profile but a large bias. Figure 19 shows the SVP for this case with a smaller horizontal scale. The overall slope is similar with similar depths and SV differences. Both profiles were evaluated as isovelocity with no deep sound channel; neither was evaluated as always upward or downward refracting.

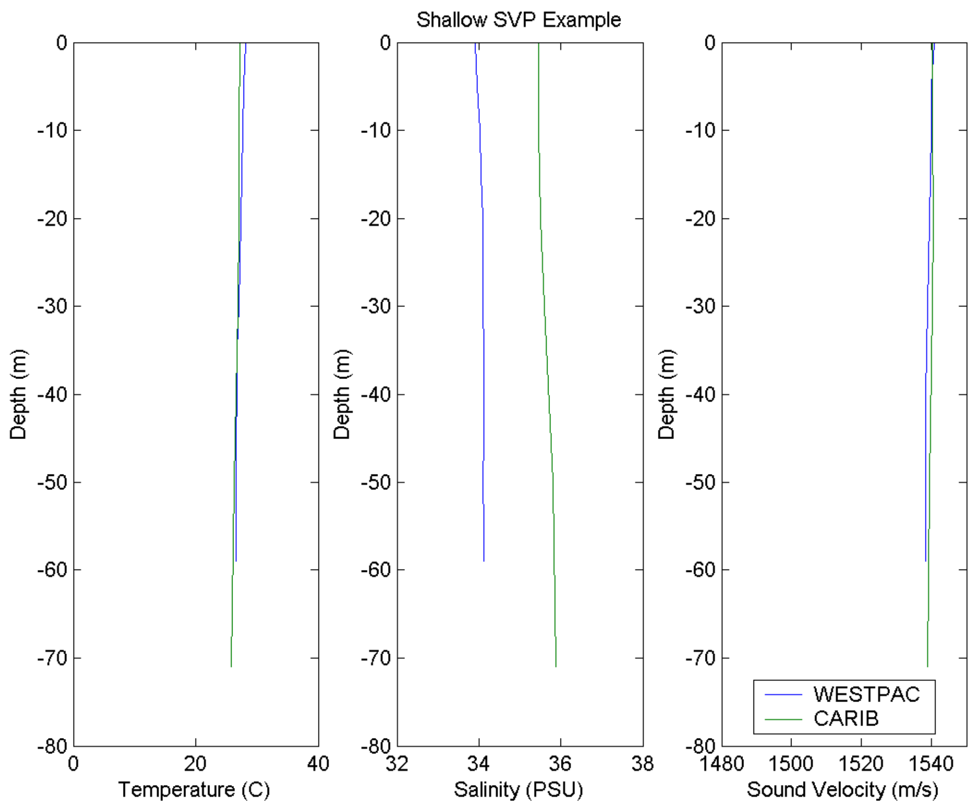

Figure 18. Highest Match Score Shallow Water Profile Comparison.

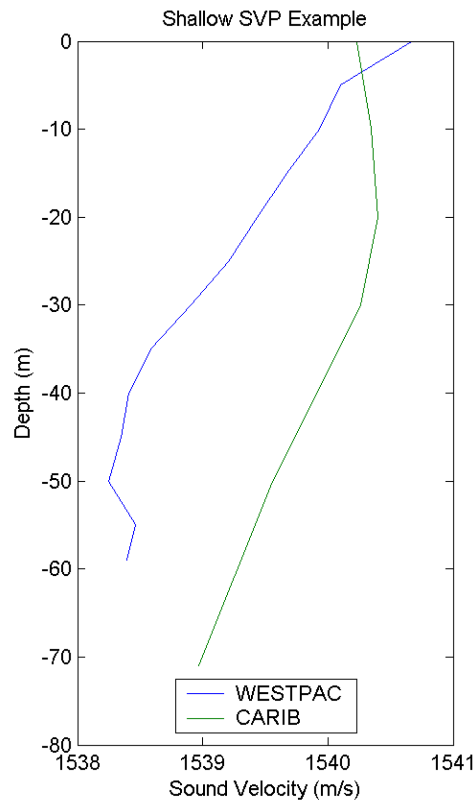

Figure 19. Highest Match Score Shallow Water SVP Comparison.

2. Low Match Score Comparison

In order to contrast the high match score areas, two areas were selected that had low match scores with the two target areas but had relatively similar bottom depths. Because similar bottom depths were maintained, the match scores for these dissimilar areas are in the 30-40% range. For the deep water case, the dissimilar area is off the coast of southern British Columbia and for the shallow water case the dissimilar area is off the coast of central California.

Figure 20 shows the temperature, salinity and sound velocity profiles for both the deep water target and the low scoring source area. The temperature, salinity and sound velocity profiles all show marked differences. The MLD, DSC depth, DSC SV, SV difference, surface temperature and maximum gamma are all different. In fact, the low score profile has no mixed layer and has a shallow secondary sound channel. Aside from the similar gamma in the pressure dominated region below 2000 m, the profiles are dissimilar.

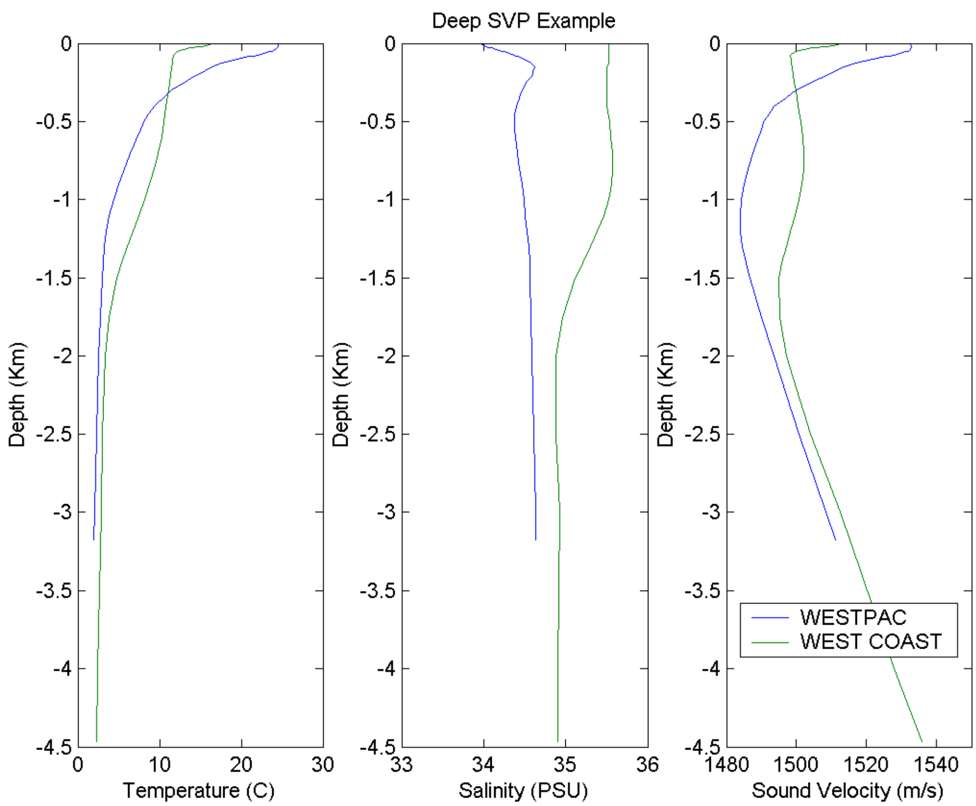

Figure 20. Low Match Score Deep Water Profile Comparison.

Figure 21 shows the temperature, salinity and sound velocity profiles for both the shallow water target and the low scoring source area. Again, note the change in vertical scale from the deep water case from km to m. The differences and slopes are similar at this scale. Both are isovelocity but there is approximately a $20^\circ C$ difference in temperature and a 50 m/s difference in sound velocity for the entire profile. Since both profiles are isovelocity, the weight of the surface temperature, mean sound velocity and sound velocity at the bottom are all increased in the heuristic logic. As a result, the fact that the these values are different in these two profiles accounts for the low match score

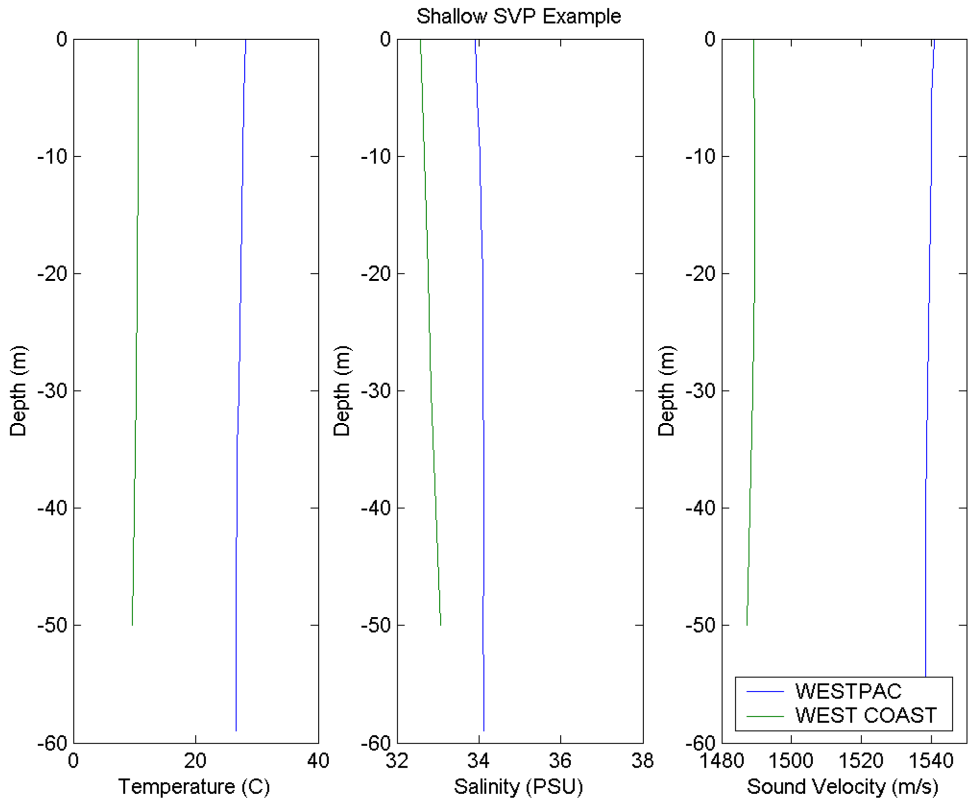

Figure 21. Low Match Score Shallow Water Profile Comparison.

G. PCIMAT PROPAGATION LOSS MODEL COMPARISON

Based on the match scores for the two highest and the two low score areas used in Section F, the PCIMAT PE propagation loss model was run at six locations for comparison. The propagation loss in two target areas of the Western Pacific were compared to the propagation losses for both the highest score areas off the East Coast and Nicaragua, and the low scores areas off the West Coast.

1. Deep Water Propagation Loss Examples

Figures 22 and 23 show PCIMAT PE propagation loss curves for the deep water target area and the highest match score source area in the CPOAS. Red indicates low propagation losses and blue indicates high propagation losses. The general shape, the shadow zone near the surface in the first three km and the high propagation loss at the bottom in the first km are seen in both curves. It is clear that these propagation loss curves demonstrate qualitatively similar energy distribution and modes of propagation.

There is a range bias between the two curves of approximately 1 km. The similarity of the propagation losses indicates that the comparison algorithm is making good comparisons. A sensitivity analysis of the weighting factors is recommended for future research to provide a more complete comparison.

Figure 24 shows the low match score example PCIMAT PE propagation loss curve. It displays very little similarity to Figure 22. It is clear that these propagation loss curves demonstrate qualitatively and quantitatively dissimilar energy distribution and modes of propagation. The three deep water propagation losses are displayed together, without legends, in Figure 25.

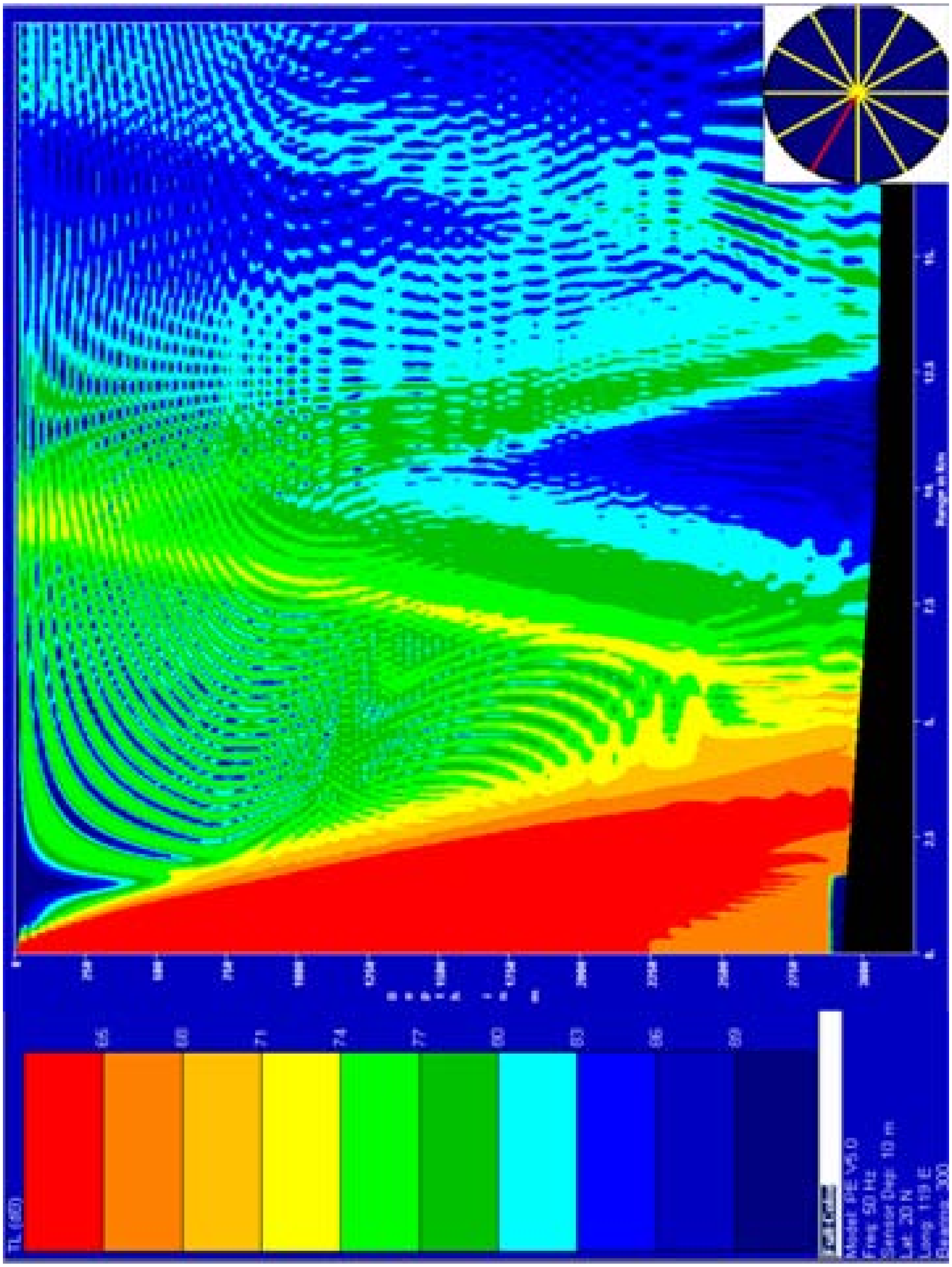

Figure 22. Deep Water Target Propagation Loss. East China Sea. [From NRaD Naval Surface Warfare Center (NRaD)].

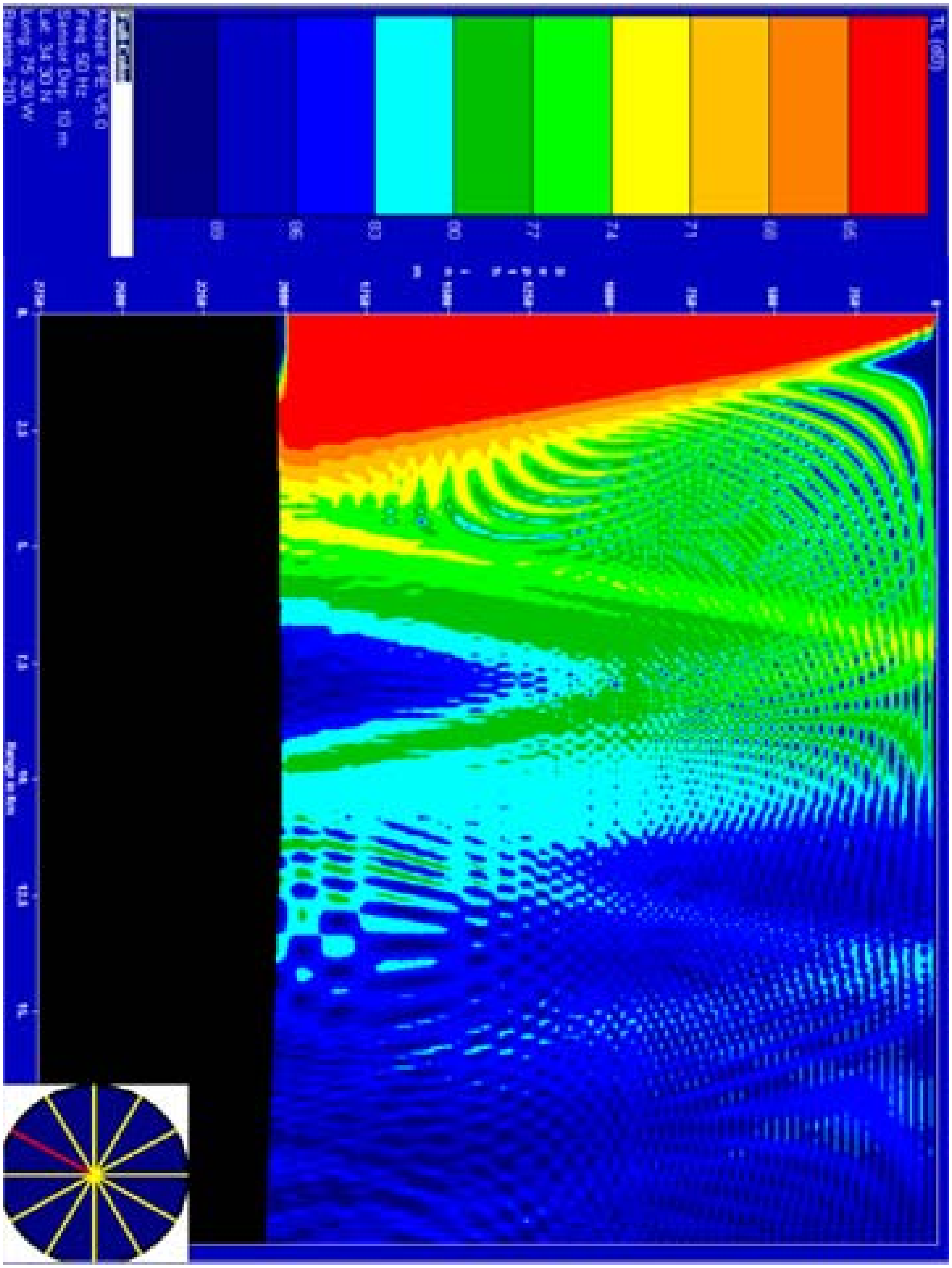

Figure 23. Deep Water Source Propagation Loss. Highest Match Score, CPOAS. [From NRaD].

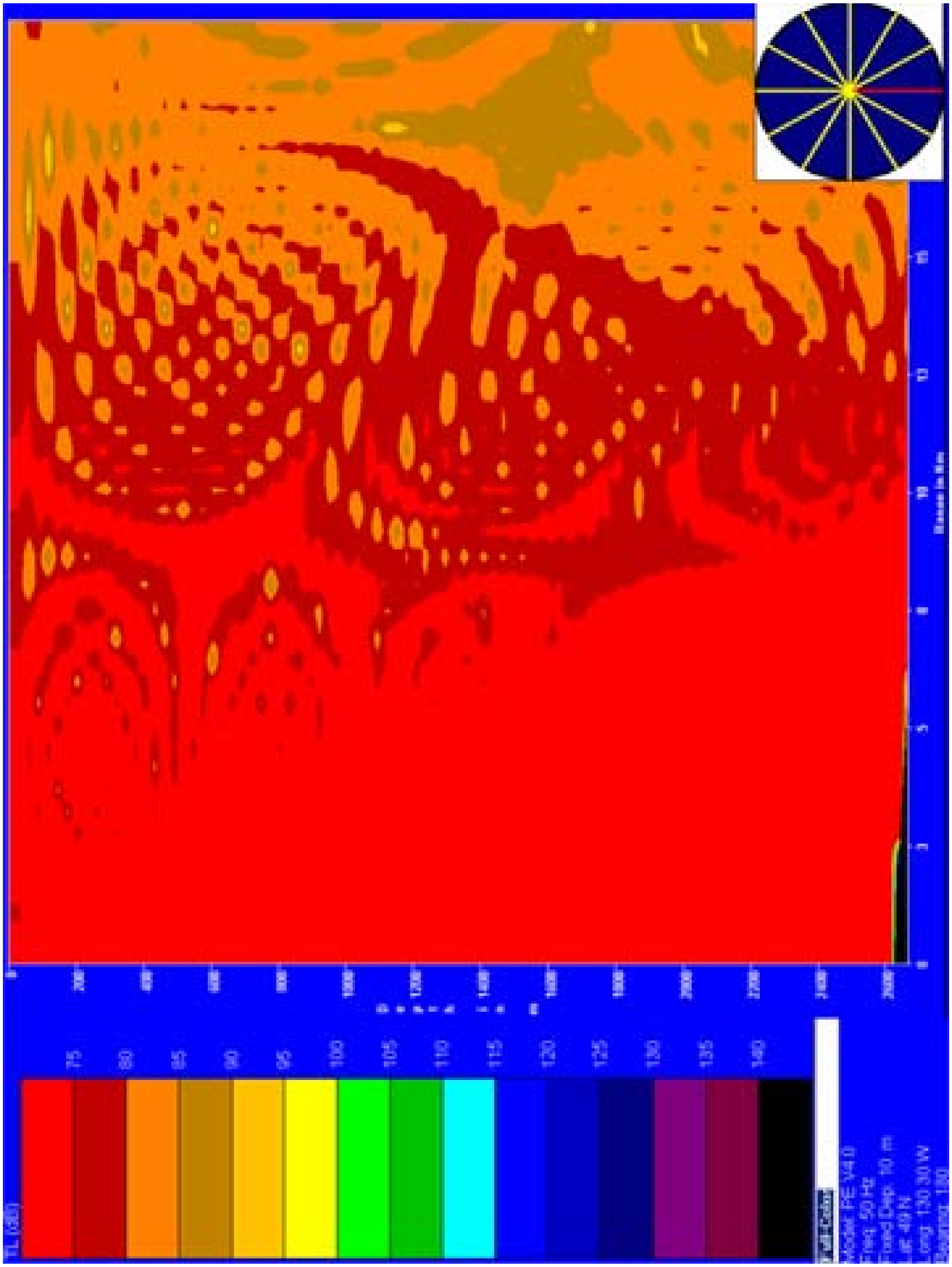

Figure 24. Deep Water Source Propagation Loss. Low Match Score, British Columbia. [From NRaD].

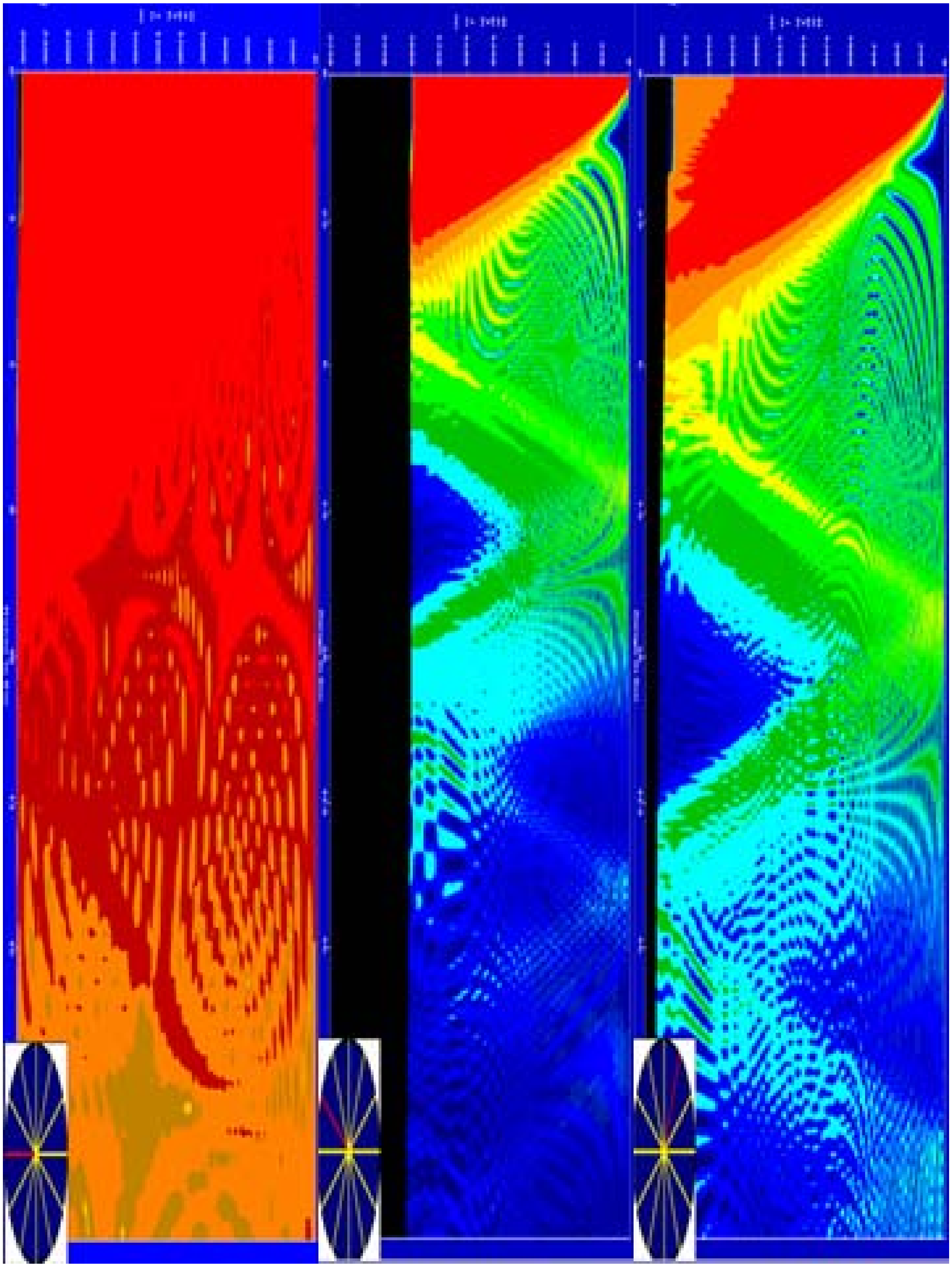

Figure 25. Deep Water Target, highest match score and low match score source propagation loss (without legend). [From NRaD].

2. Shallow Water Propagation Loss Examples

Figure 26 and 27 show PCIMAT PE propagation loss curves for the shallow water target area and the highest match score source area in the JAXOAS. The general shape and banded energy distribution are similar in both curves. It is clear that these profiles demonstrate similar energy distributions and modes of propagation. There is a range bias between the two of 1 to 3 km. As with the deep water example, the similarity of the propagation losses indicates that the comparison algorithm is making good comparisons and a sensitivity analysis of the weighting factors is recommended for future research to provide a more complete comparison.

Figure 28 shows the low match score example PCIMAT PE propagation loss curve from the central coast of California. It displays a similarity in banded structure in the upper 30 m to Figure 26, but the differences in the magnitude of propagation loss between the two shows a quantitative difference. These profiles demonstrate dissimilar energy distribution and modes of propagation, especially below 30 m. The three shallow water propagation losses are displayed together, without legends, in Figure 29.

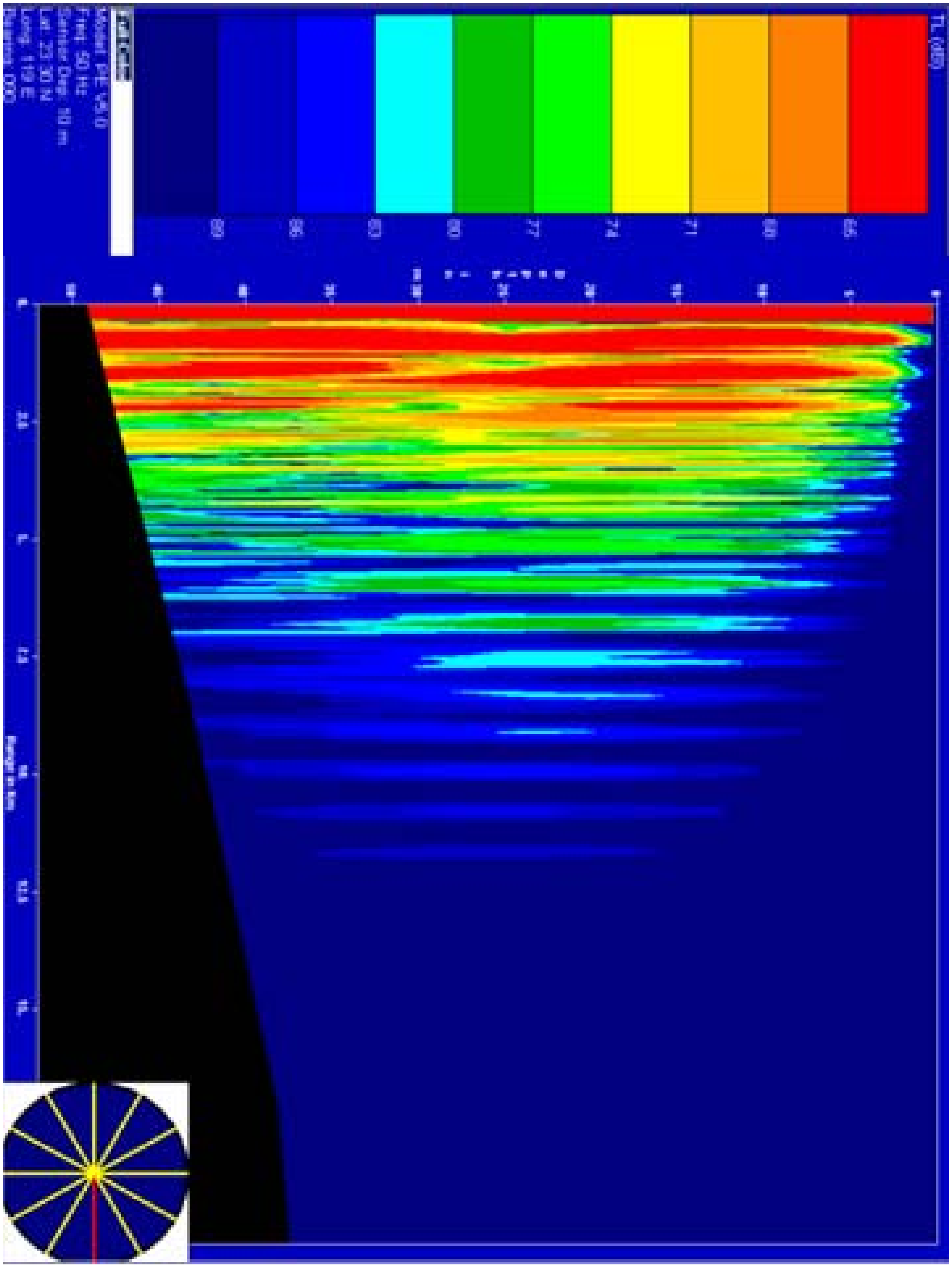

Figure 26. Shallow Water Target Propagation Loss. East China Sea. [From NRaD].

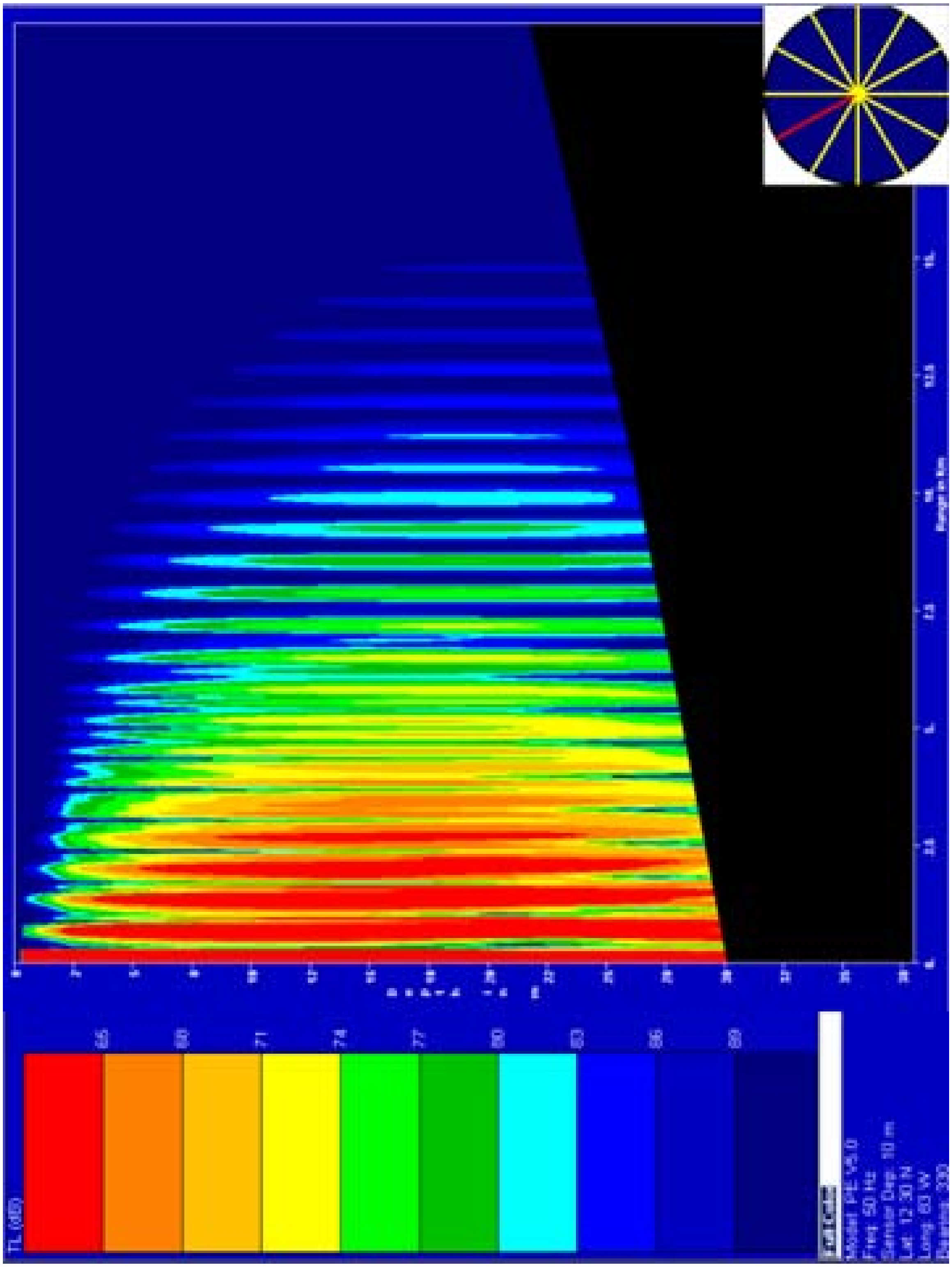

Figure 27. Shallow Water Source Propagation Loss. Highest Match Score, Nicaragua. [From NRaD].

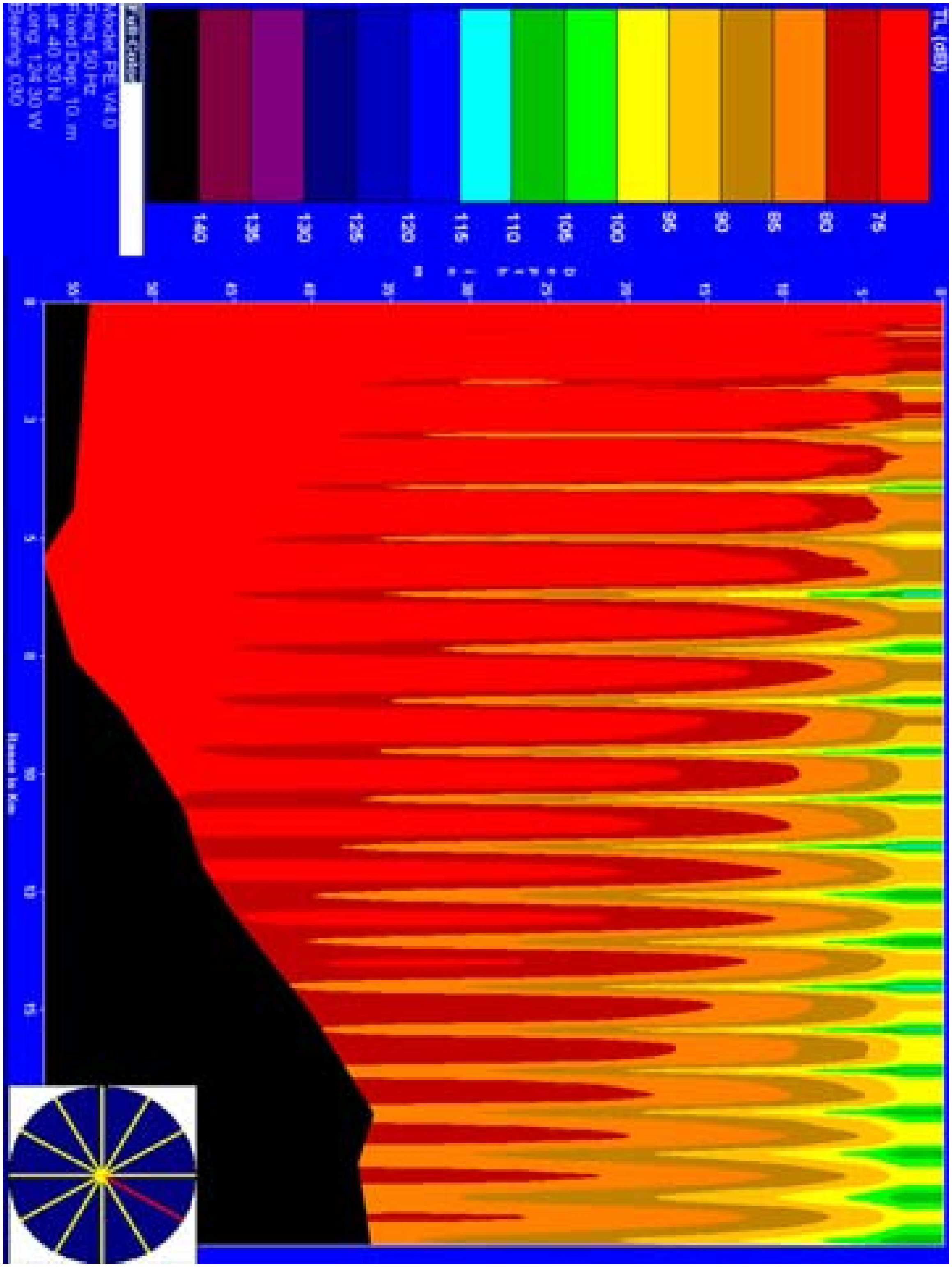

Figure 28. Deep Water Source Propagation Loss. Low Match Score, Central California. [From NRaD].

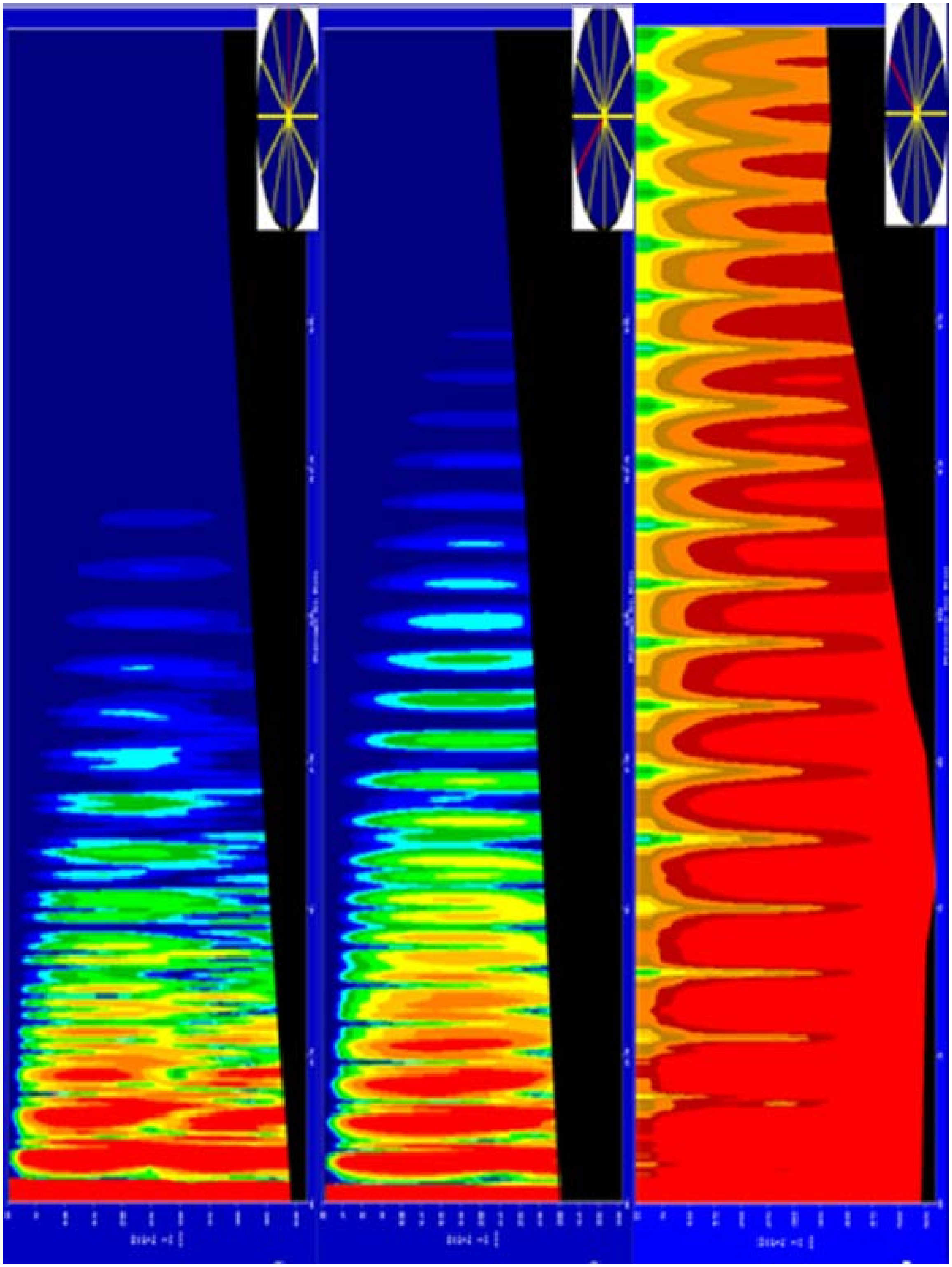

Figure 29. Shallow Water Target, highest match score and low match score source propagation loss (without legend). [From NRaD].

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VI CONCLUSIONS

The process and algorithms used in this project highlight the need to accurately characterize physical ocean environments to the extent that they are operationally similar for the purpose of analog determination. As discussed in Chapter IV, an accurate physical description is all that is required, and not a model of the physical processes within the environment. With this in mind, research into the data available has determined that data exists for many acoustic and non-acoustic characteristics that can be used for area comparison and the example process showed that these were adequate for a quantitative comparison The process can be refined through sensitivity analyses conducted on the weighting factors and heuristic rules.

The method used for comparison in the example process is fuzzy logic. The choice of fuzzy logic was influenced by its use by Robert Miyamoto in the ESA. Because the fuzzy entropy calculations use the inherent distribution of each property within the sample space for fuzzy set membership, the process eliminates the need for statistical modeling of the data distribution. The use of heuristic rules to adjust weights, also a fuzzy logic concept, allows for a quantitative vice qualitative comparison for operational purposes. For these reasons, this project has demonstrated that fuzzy logic concepts offer a valid approach for quantitative comparison

The six PCIMAT model output comparisons and the SVP comparisons were included as a check of the accuracy of the process in determining operationally similar areas. The results showed that a reasonable set of hypothetical weights and heuristic rules yielded similar sound velocity profiles and propagation loses for both deep water and shallow water examples.

The example process developed in this project was an attempt to show that the hypothesized physical description and comparison of ocean areas to determine USW Analog Areas is possible using the databases and processing tools available today. The final conclusion of this thesis is that it is possible to characterize the physical ocean environment and compare different ocean areas in an operationally meaningful way. With the result that USW Area Analogs can be found.

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VII RECOMMENDATIONS FOR FOLLOW ON RESEARCH

This thesis has established and validated to first order a process to compare ocean areas for analog determination. Future research will refine this process and provide fleet planners with a software product capable of analog identification. This tool may be used to develop a tailored USW Area Analog product for the fleet or mature into a TDA for analog evaluation.

A. IMPROVE THE EXISTING PROCESS

The process outlined in Chapter V does not have the capability to characterize a secondary sound channel. Adding this capability would require the addition of several more descriptors and heuristic rules but would otherwise be straightforward.

The "downward refracting" binary check is not currently used. The incorporation of this binary check into additional heuristic logic steps would better characterize this type of SVP.

Increasing the area of coverage for comparison to include target areas will allow the algorithm to determine the extent of the region that a given target profile comparison is valid. A global comparison will allow the use of overseas areas as source areas and will allow a reverse comparison. Areas that are currently used for training could be compared to overseas areas to determine which overseas areas are most like the training areas.

Adjusting the sample space using the shallow water binary tests to compare only those areas that display shallow characteristics would allow for a different statistical distribution of shallow water characteristics and may improve littoral comparisons. This would affect fuzzy set membership and therefore fuzzy entropy calculations. The use of a smaller source area would also test the limits of the process with respect to sample space size. Improved vertical resolution may be required to make this approach practical.

B. SENSITIVITY ANALYSIS OF THE WEIGHTING FACTORS AND HEURISTIC RULES

In order to improve the accuracy of the example output, a systematic sensitivity analysis of the weighting factors and heuristic rules is required. This study would determine if the parameters are adequate for the description, as well as those parameters which do not affect the comparison and can therefore be eliminated. Most importantly, it would provide a basis for the choice of weights.

C. INCORPORATE ADDITIONAL DATA TYPES

The incorporation of higher resolution data in the form of unprocessed SVPs will help to improve the vertical and temporal resolution of the output. The variability of the various descriptive parameters may also be used for comparison. For example, the variation of the MLD over a weekly period could be used a descriptor of ocean variability in an area. A re-examination of the method used to determine MLD should also be considered when higher resolution data is incorporated. The development of an optimum interpolation method will be required to allow consolidation of unprocessed data to gridded locations.

A separate bathymetry database like ETOPO2 will be required if unprocessed SVP data without soundings is used. Additional descriptors derived from bathymetry, like bottom slope, could then be incorporated.

Another data source that could be used to improve the temporal resolution is the MODAS dynamic climatology archive. The daily, satellite data corrected, SVP fields could be used to improve the temporal resolution to daily or weekly vice monthly. Since this data is gridded at the same vertical and horizontal resolution as GDEM, the current process could be used for processing.

Adding LFBL data or its derivative, the CBLUG data set, would improve the accuracy of the bottom characterization. The addition of the HFBL data set would allow for mine warfare and high frequency sonar applications.

Incorporating background noise data from the various NAVOCEANO databases will continue to improve the acoustic characterization. Since this parameter can sometimes dominate the acoustic environment, careful weighting and heuristics may be required to ensure operational applicability.

D. EXPAND TO OTHER MISSION TYPES

Adjusting the weights and heuristic logic for different mission types would be a relatively easy addition to the process. Only the weights and rules would need to be altered and the fuzzy entropies calculated for display. Some mission types would require additional data. For example, Mine Warfare (MIW) would require the addition of HFBL data and the NGDC Coastal Relief Model. Intelligence Surveillance and Reconnaissance (ISR) would require atmospheric factors.

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APPENDIX A. ADDITIONAL COMPARISON METHODS

Several methods of processing and comparing environmental data were attempted or considered during the development of the example process in Chapter V. Among these were the use of ArcMap to consolidate SVPs and the use of unprocessed SVPs from CTD data in the WOD01.

A. USING ARCMAP TO CONSOLIDATE DATA

As a GIS, ArcMap has many tools that enable the manipulation of geocoded data including many database functions like query building and sorted data output.

Data derived from WOD01 unprocessed SVPs was loaded into ArcMap and selected manually in an area approximately the size and shape of an OPAREA. The "OPAREA" data was output to a new file and imported back into MATLAB. The process was time consuming because it required multiple file conversions in Excel. The primary reason that this method was chosen was that it allowed data to be selected from an area that was in an irregular shape like that of some OPAREAs. For the reasons stated in Chapter IV Section C, the use of gridded data instead of pre-selected areas eliminated the need to import data into ArcMap for area determination.

B. PROCESSING UNPROCESSED SVP DATA

The use of unprocessed data added significant complexity to the SVP evaluation process because it required some of the same work that is required to grid the data. Although MATLAB code was developed for the use of unprocessed SVP data, this code was not used in the process example. An outline of the process of deriving descriptive data from WOD01 CTD data is included in the discussion below as an outline for further research.

Data extraction was via a preprogrammed FORTRAN executable. This program produced a set of SVP data in depth, temperature and salinity with header information containing latitude, longitude and the date the data was taken. Two key pieces of metadata are missing from this extraction and the FORTRAN program must be modified to provide them in the future. The depth sounding at the location the data was taken and the number of lines in the SVP data are not included in the extraction. The addition of these two pieces of information will greatly simplify the descriptive data calculations.

MATLAB code is written to process unprocessed SVP data as extracted by the pre-programmed executable as follows:

Data is read in line by line using the % symbol as an identifier that a new SVP is starting. The % character is used as a header line identifier. Since there is no line count available for each SVP, all the data in the file is saved in cell matrices with the descriptive position and date data in a separate cell from the SVP profiles. A cell matrix is a matrix that can contain any type of data as individual elements, even other matrices.

The descriptive parameters were determined for each SVP and the new descriptive data added to the descriptive data cells. The methods for characteristic determination were the same as described in Chapter III. The SVPs were purged from their cells as they were processed. Because the SVPs did not contain bottom data, and bathymetry from another source was not used at this stage, the bottom SV and SV excess were not calculated. Error checking was not developed.

This process had several disadvantages. The memory required to hold all the SVPs at once was enough to slow computer processing dramatically. Rewriting the extraction code to include bottom depth and the number of lines of SVP data will allow the program to run faster and for a full SVP profile, including bottom SV and SV excess, to be described.

APPENDIX B. DEEP WATER EXAMPLE MONTHLY ATLAS

The ArcMap output examples in Chapter V only showed the highest monthly match score for each location. This simplified the examination of high match score areas on a single plot. In order to examine the temporal aspects of the comparison process, a set of 12 monthly match score plots for the deep water case are included as an example of an annual atlas in Figures 30 through 41. The target SVP between Luzon and the continental shelf is for January.

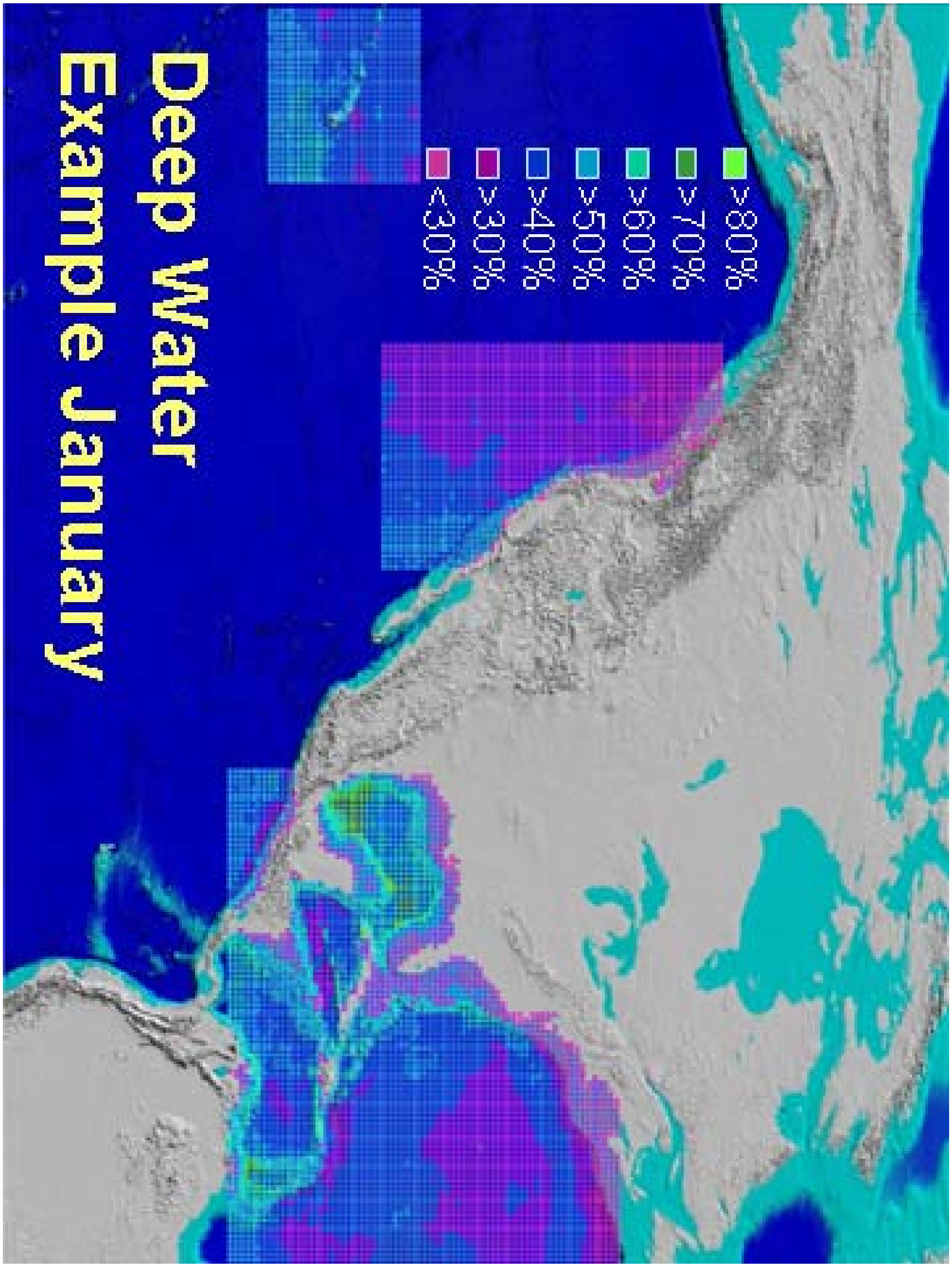

Figure 30. January Deep Water Color Contoured Match Score. [After ArcIMS].

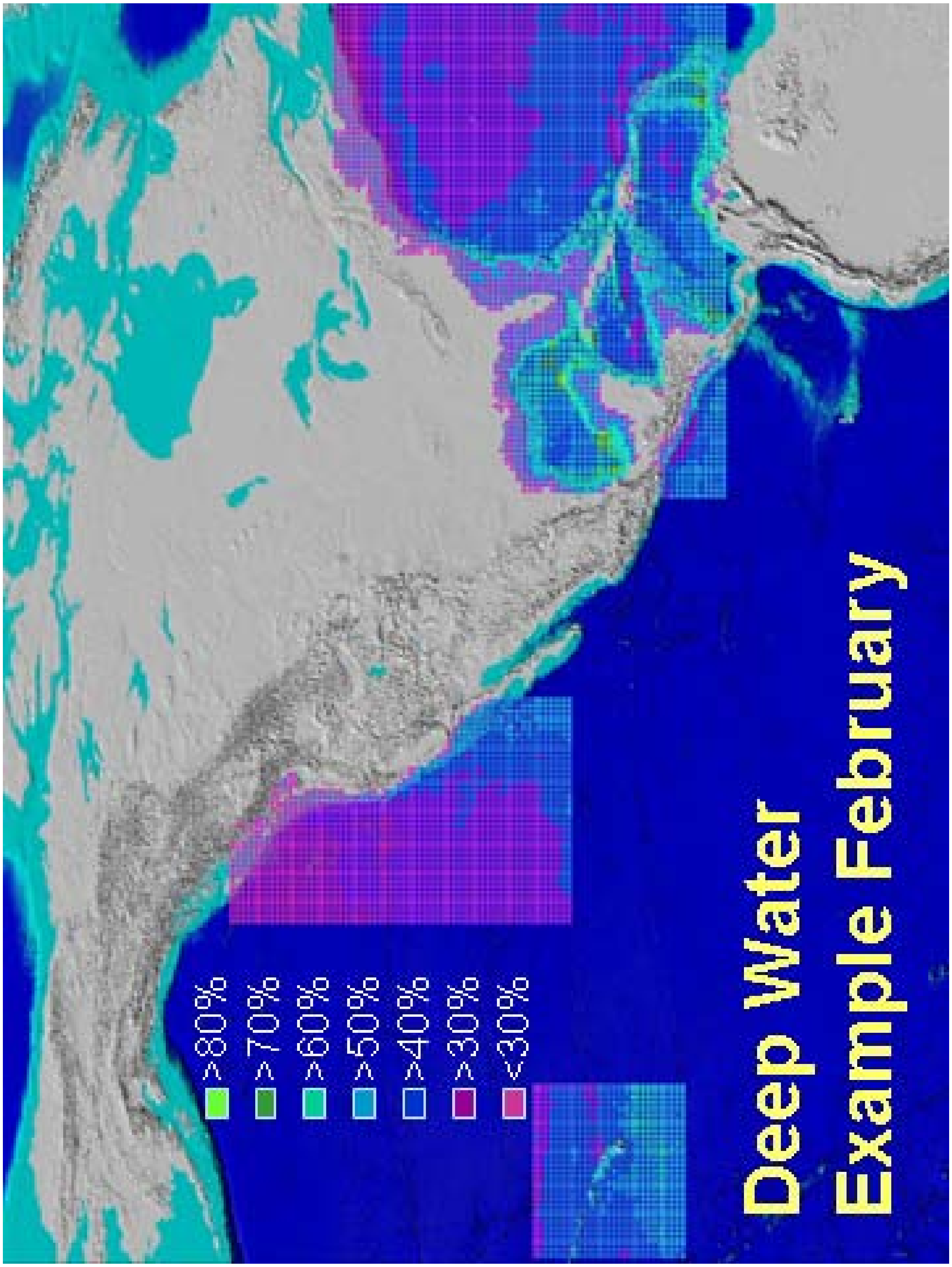

Figure 31. February Deep Water Color Contoured Match Score. [After ArcIMS].

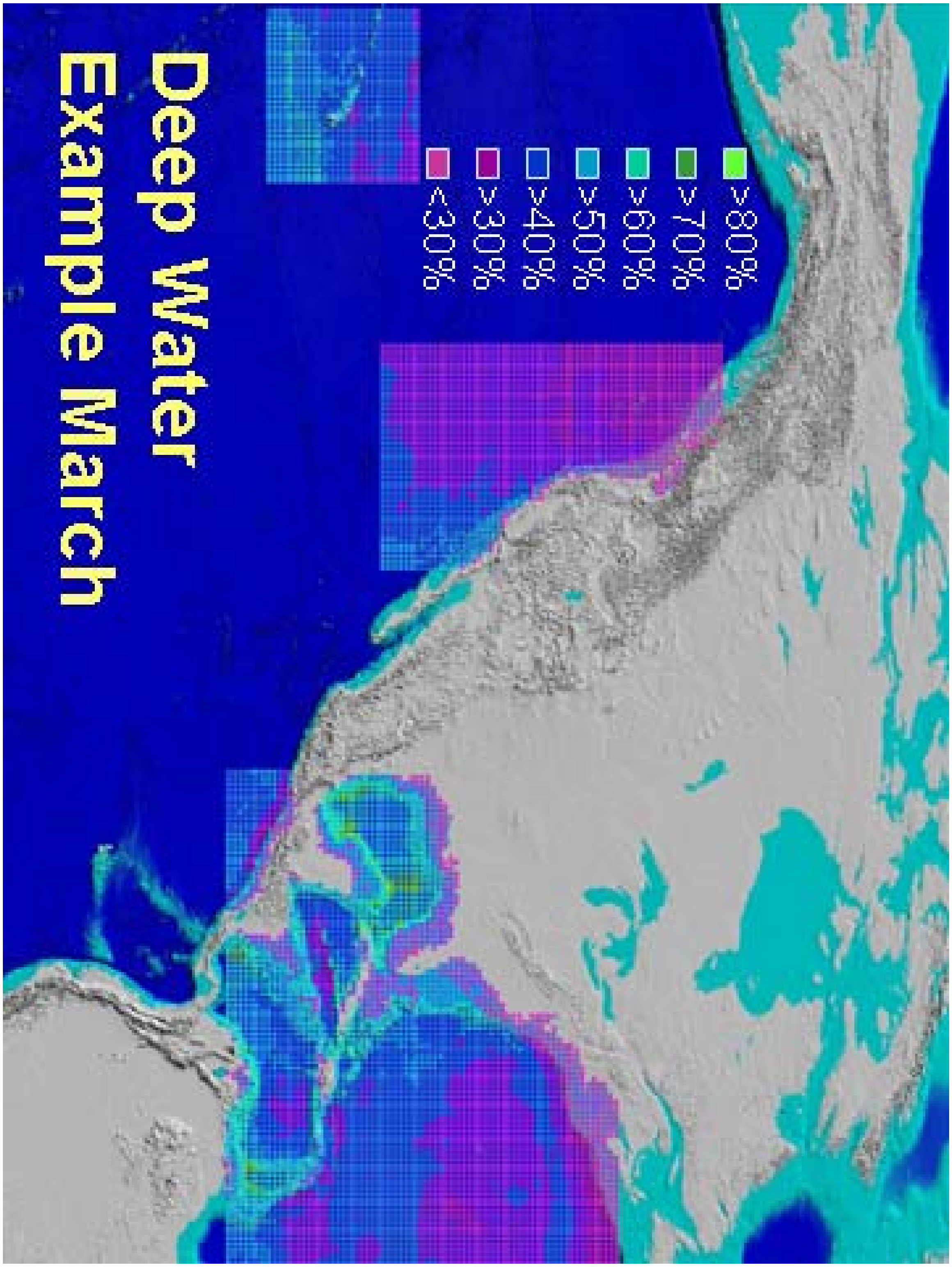

Figure 32. March Deep Water Color Contoured Match Score. [After ArcIMS].

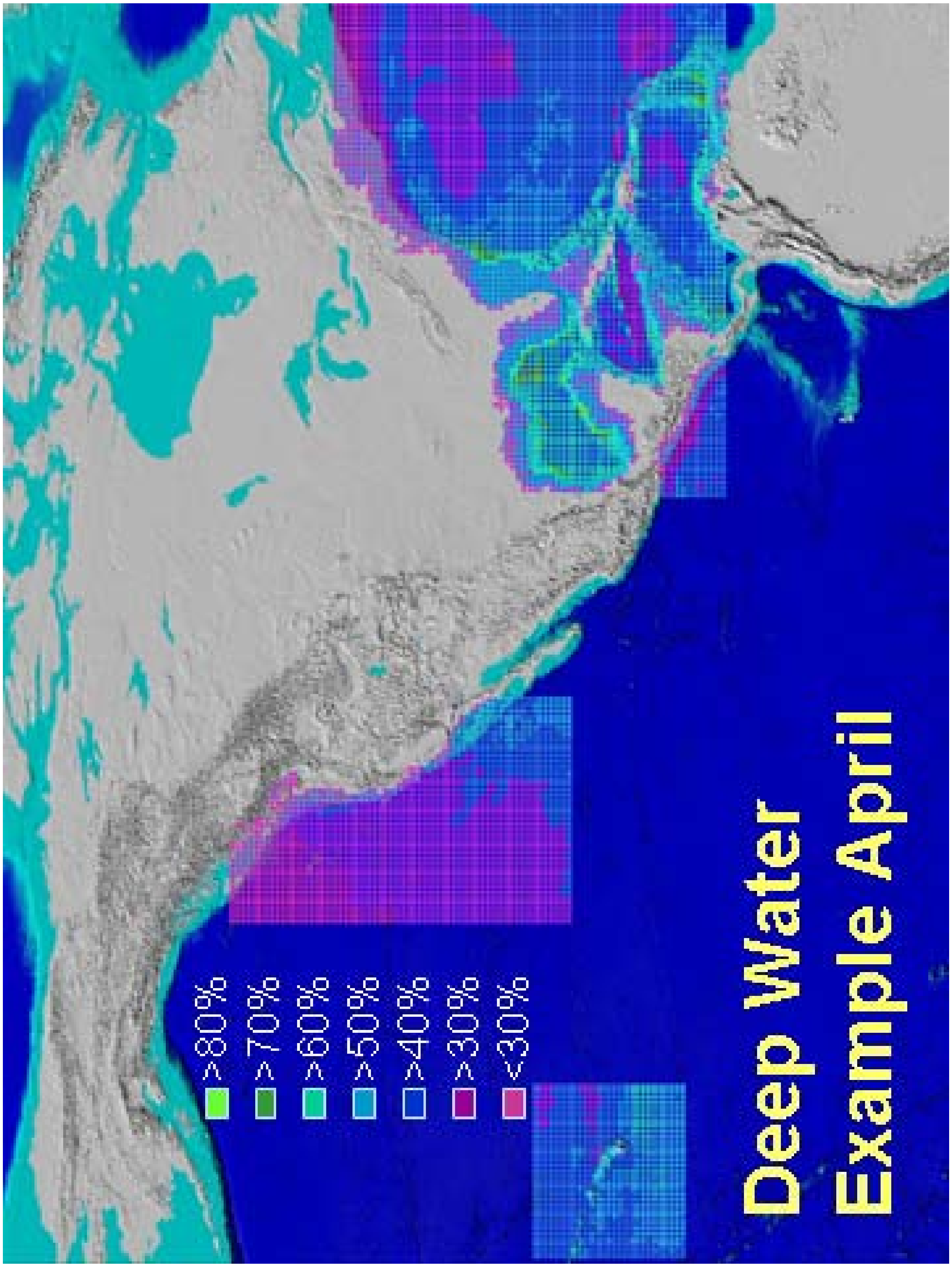

Figure 33. April Deep Water Color Contoured Match Score. [After ArcIMS].

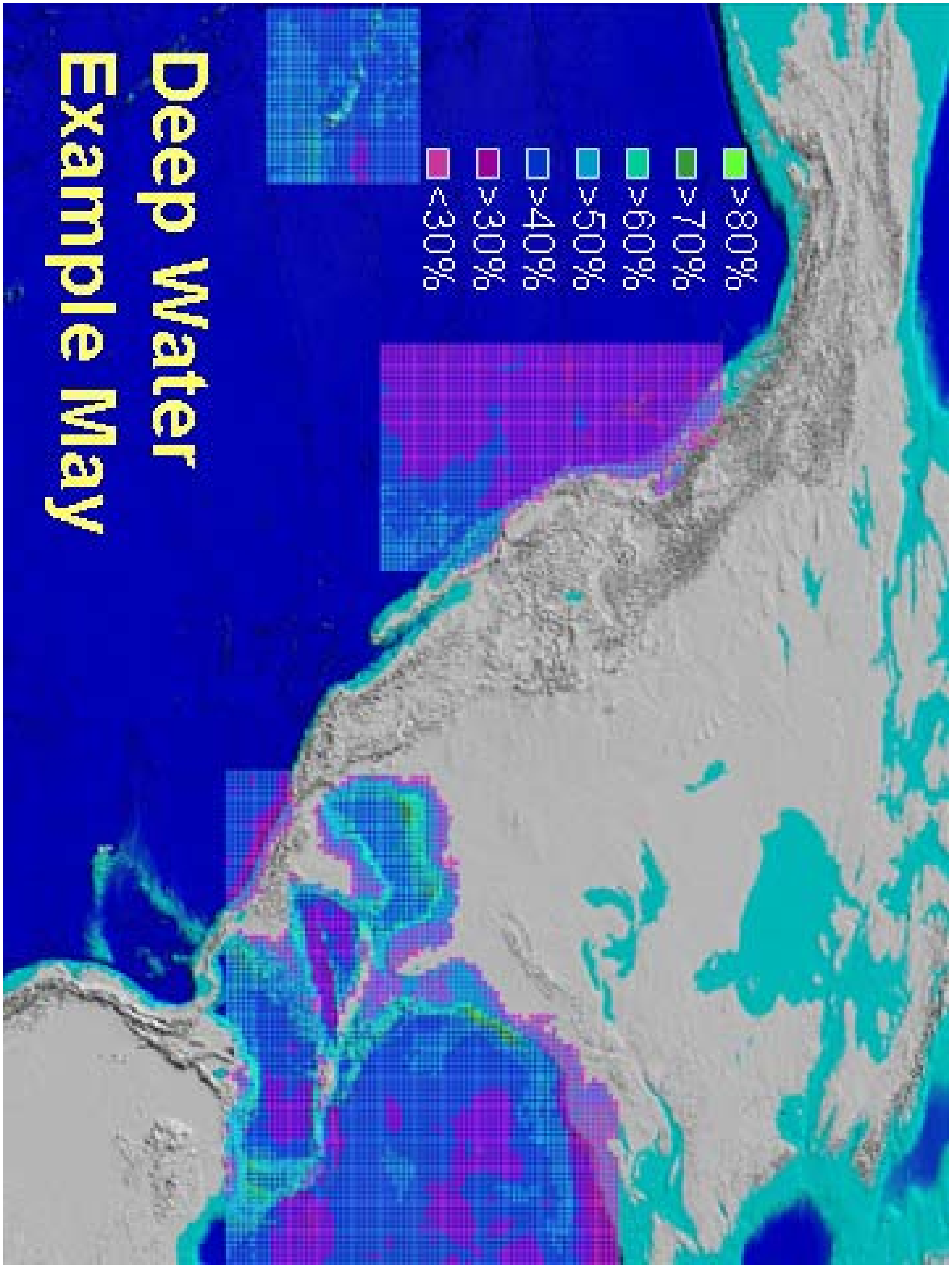

Figure 34. May Deep Water Color Contoured Match Score. [After ArcIMS].

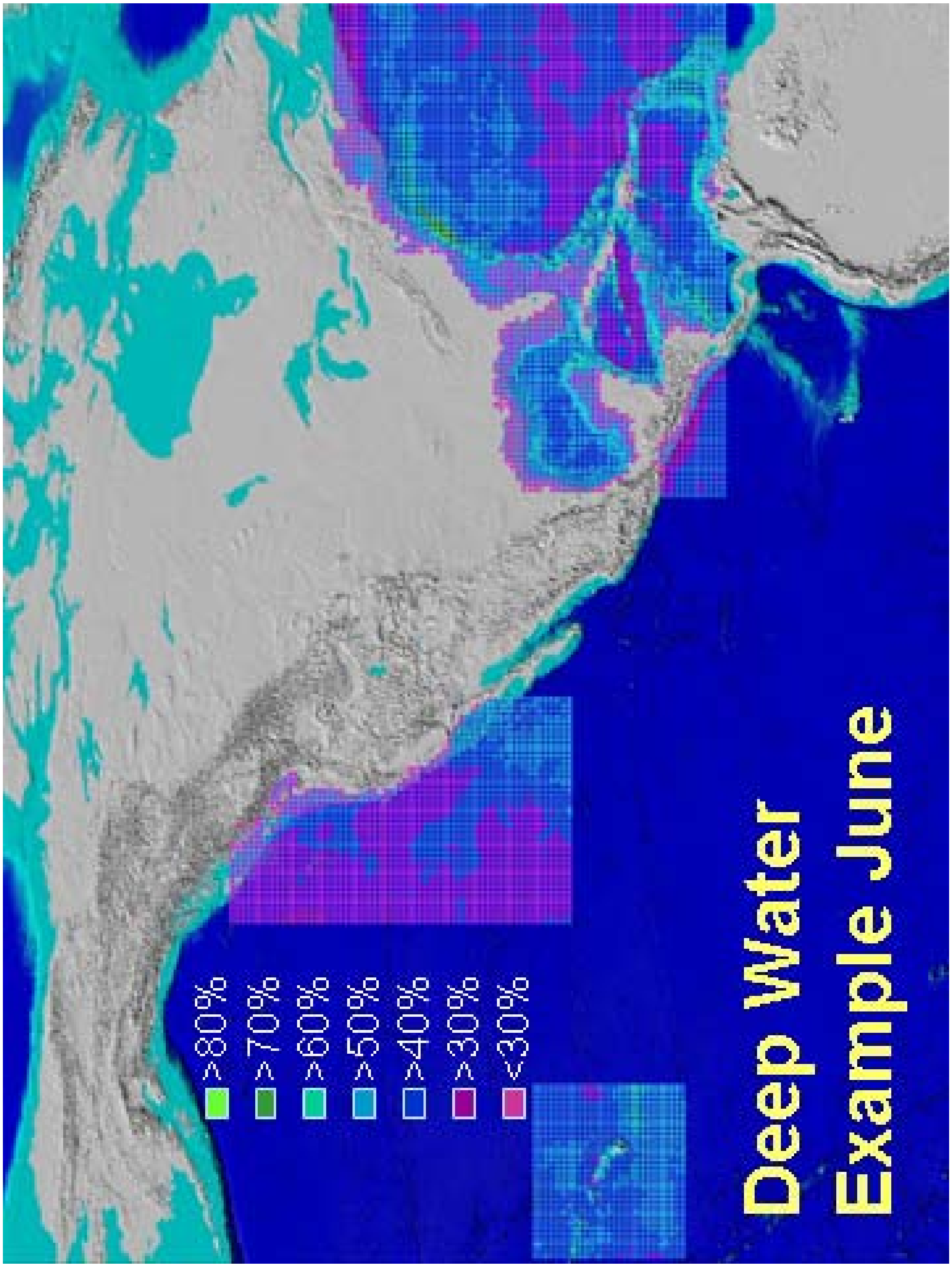

Figure 35. June Deep Water Color Contoured Match Score. [After ArcIMS].

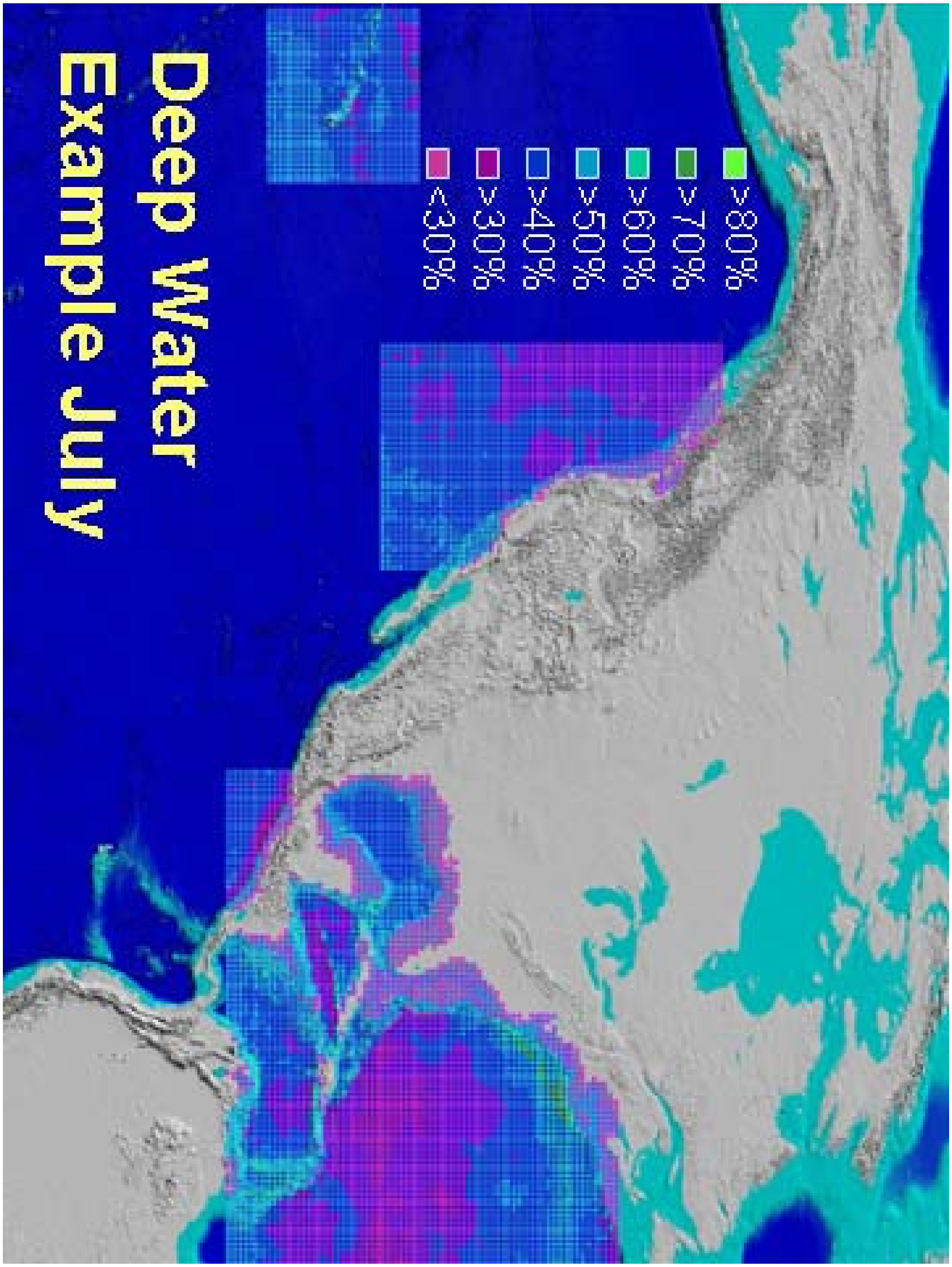

Figure 36. July Deep Water Color Contoured Match Score. [After ArcIMS].

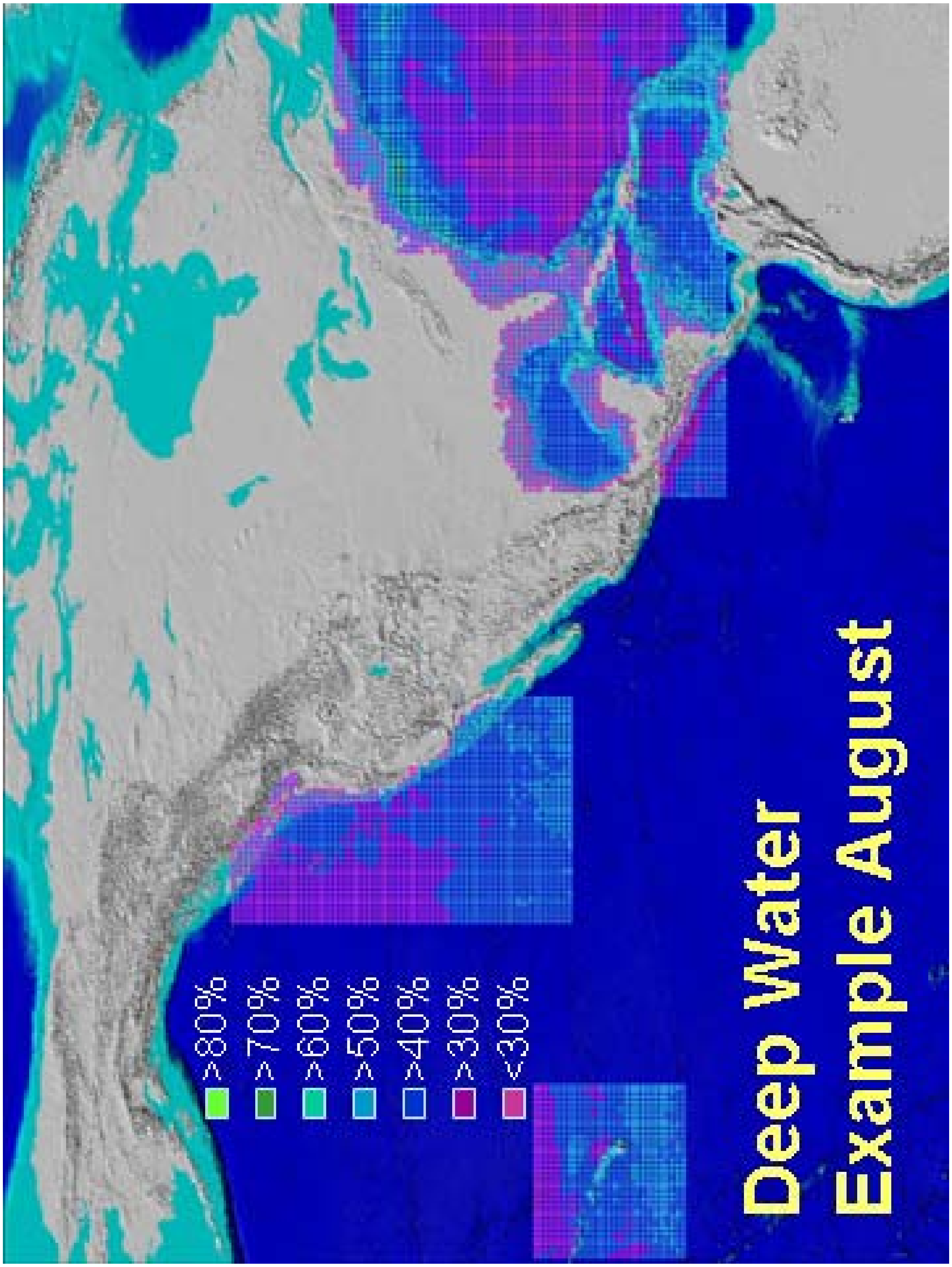

Figure 37. August Deep Water Color Contoured Match Score. [After ArcIMS].

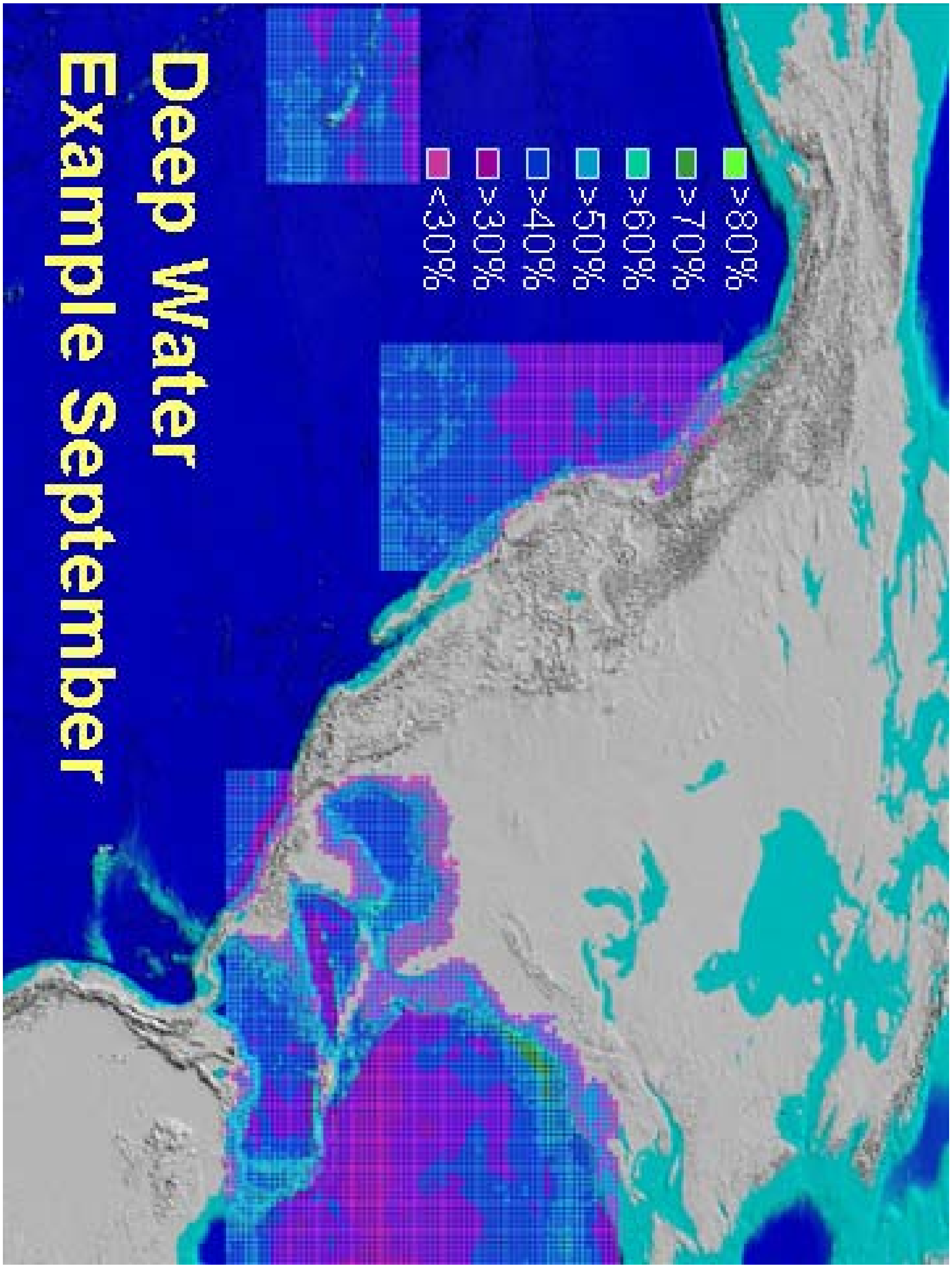

Figure 38. September Deep Water Color Contoured Match Score. [After ArcIMS].

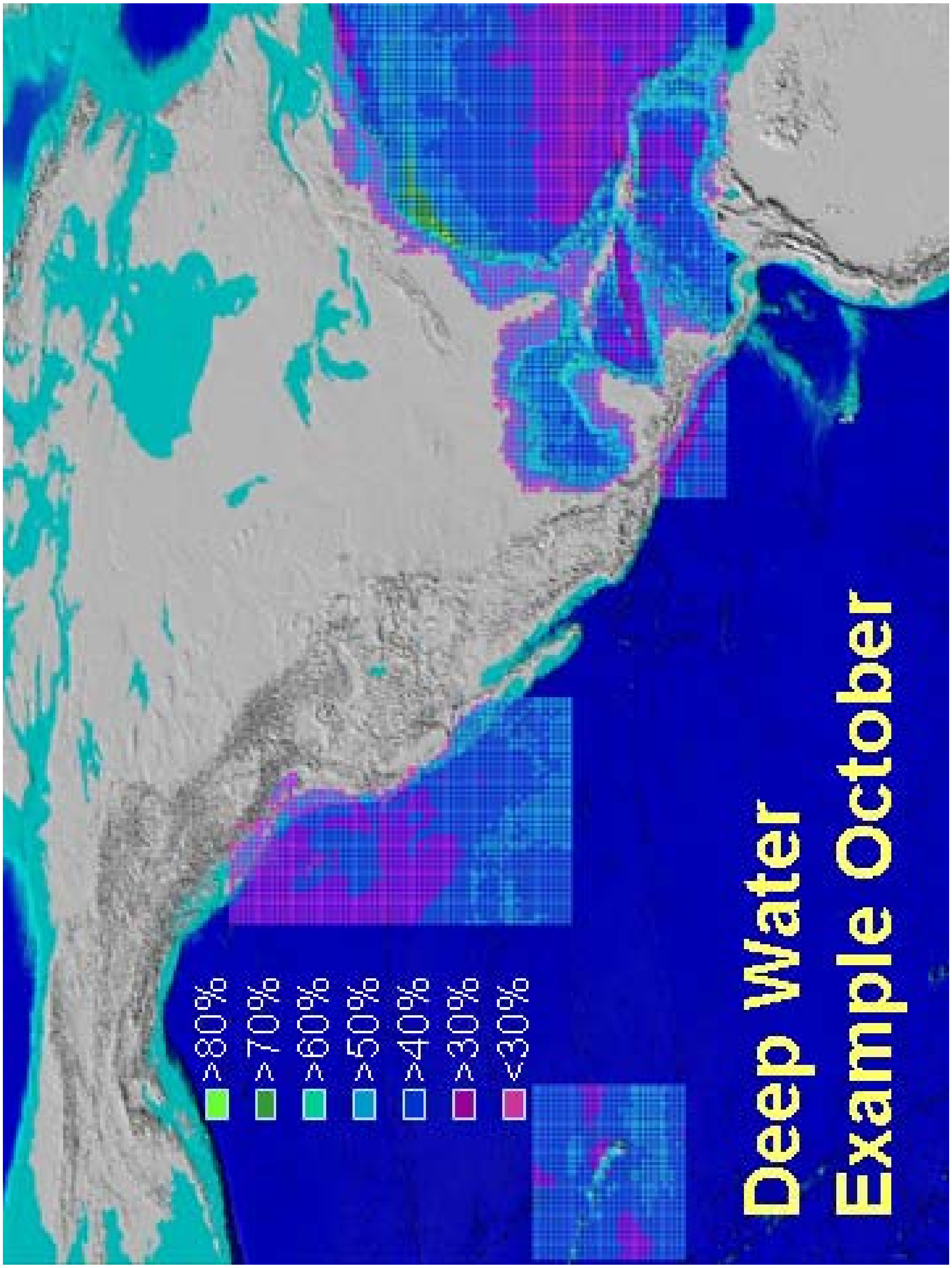

Figure 39. October Deep Water Color Contoured Match Score. [After ArcIMS].

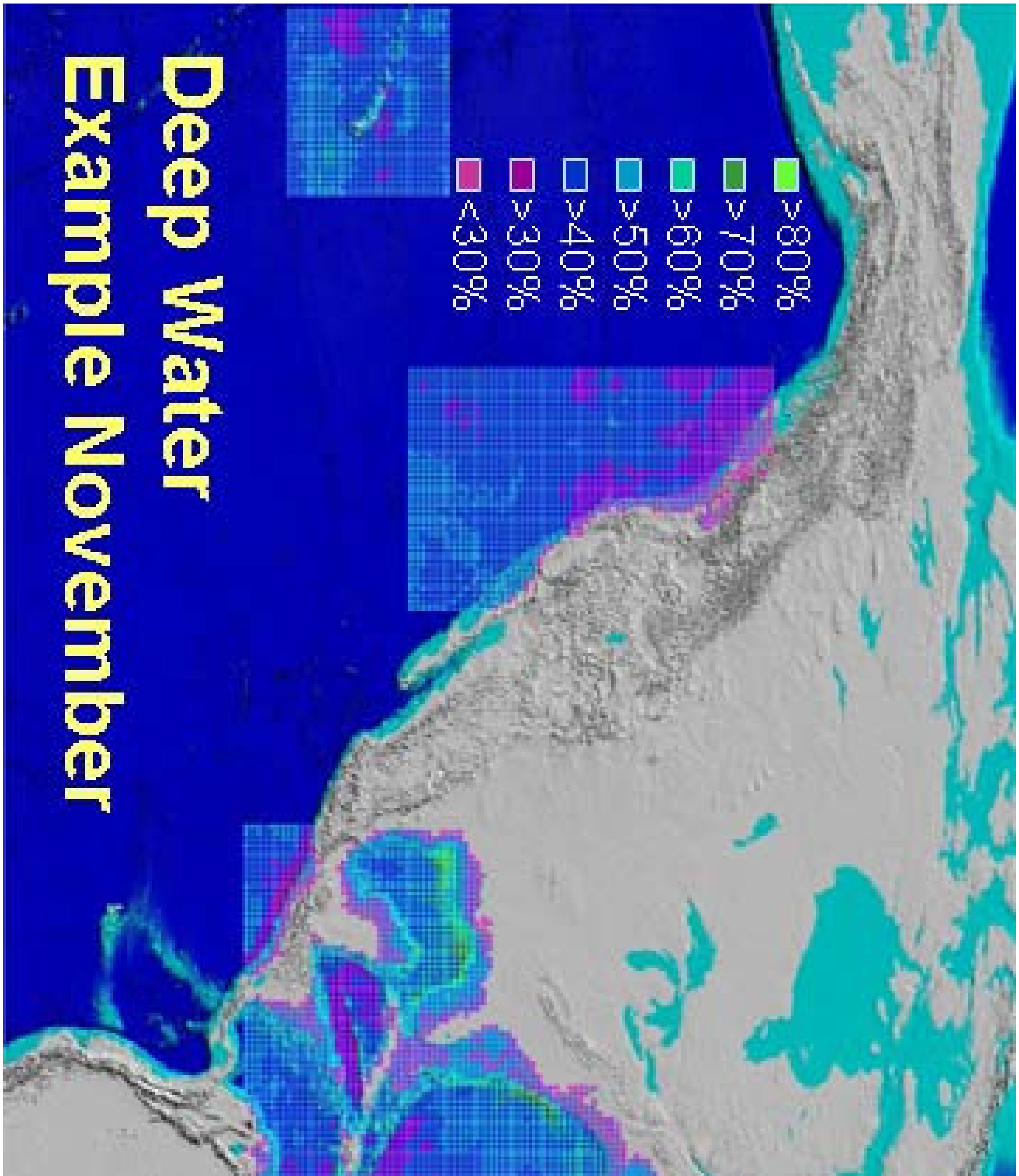

Figure 40. November Deep Water Color Contoured Match Score. [After ArcIMS].

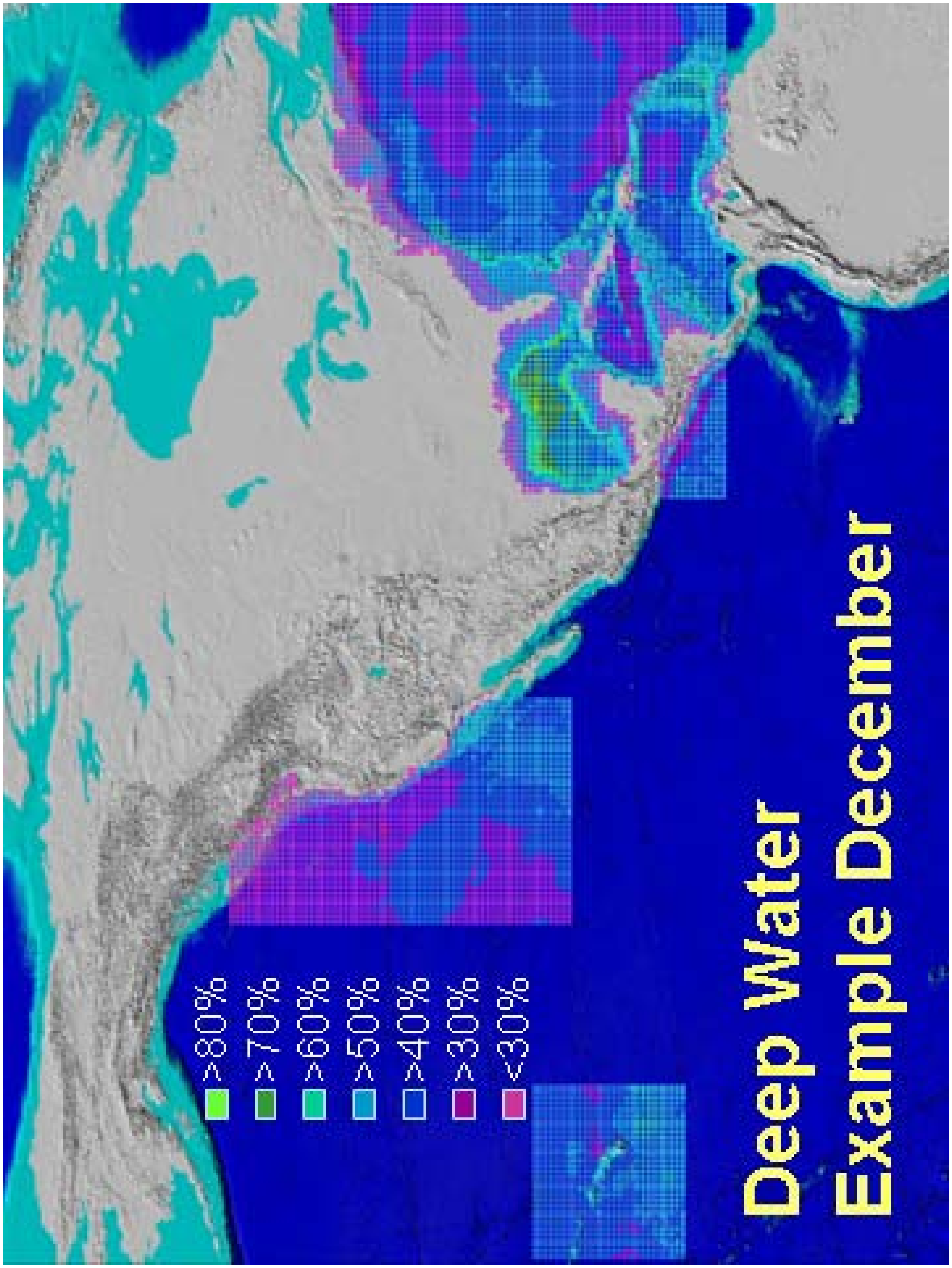

Figure 41. December Deep Water Color Contoured Match Score. [After ArcIMS].

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APPENDIX C. SHALLOW WATER EXAMPLE MONTHLY ATLAS

In order to examine the temporal aspects of the comparison process for the shallow water case, a set of 12 monthly match score plots are included as an example of an annual atlas in Figures 42 through 53. The target SVP in the Taiwan Strait is for September.

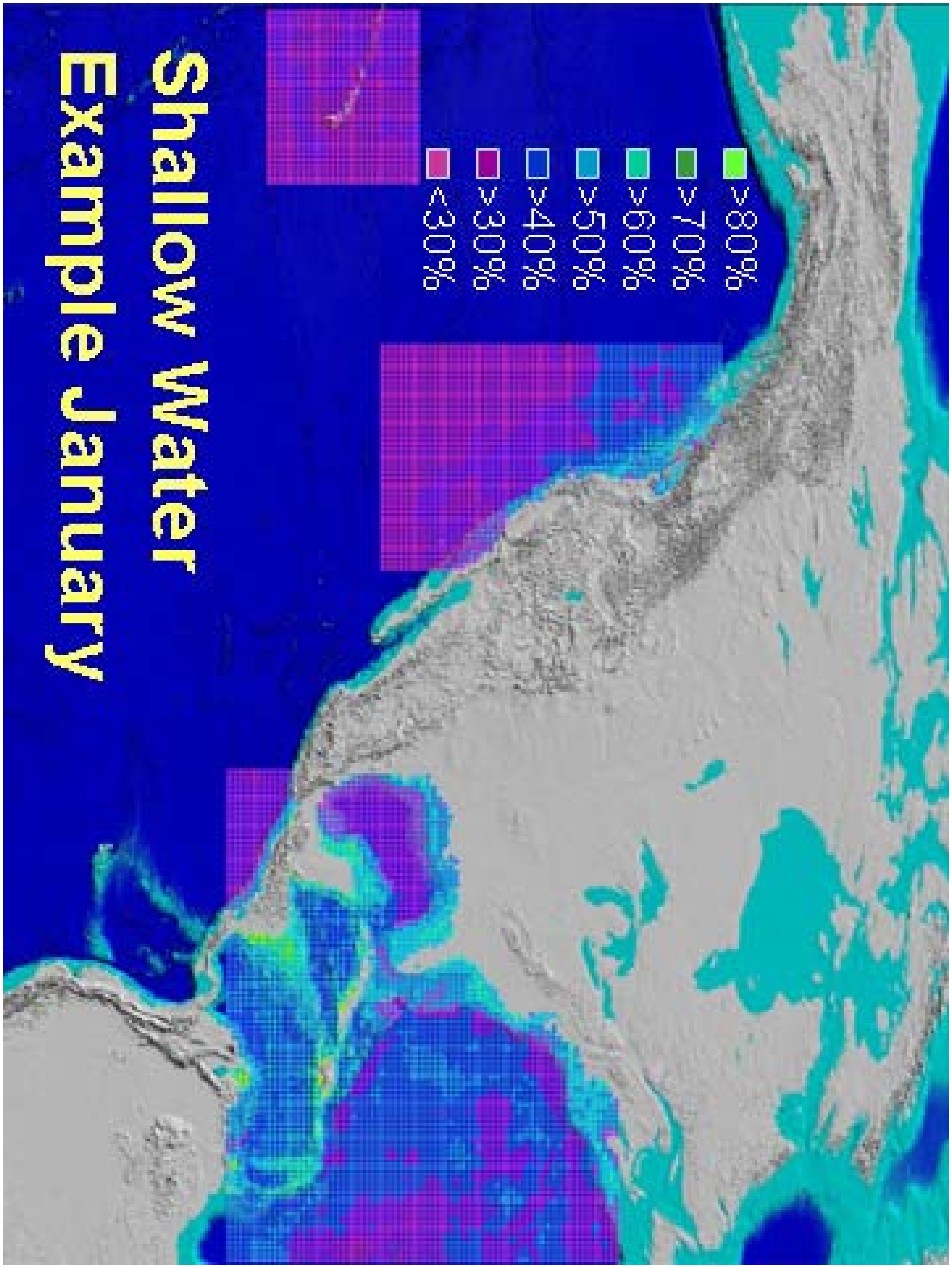

Figure 42. January Shallow Water Color Contoured Match Score. [After ArcIMS].

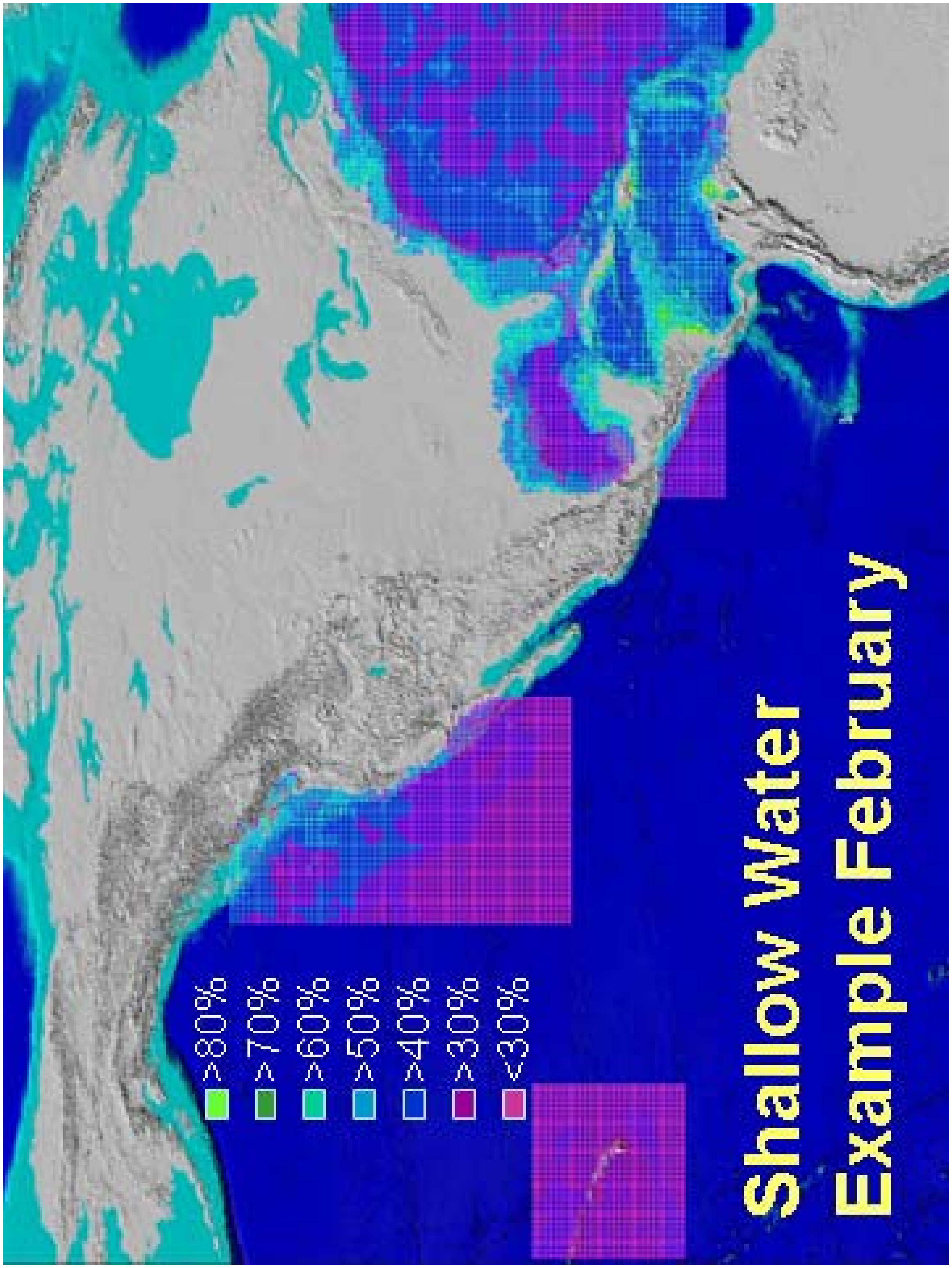

Figure 43. February Shallow Water Color Contoured Match Score. [After ArcIMS].

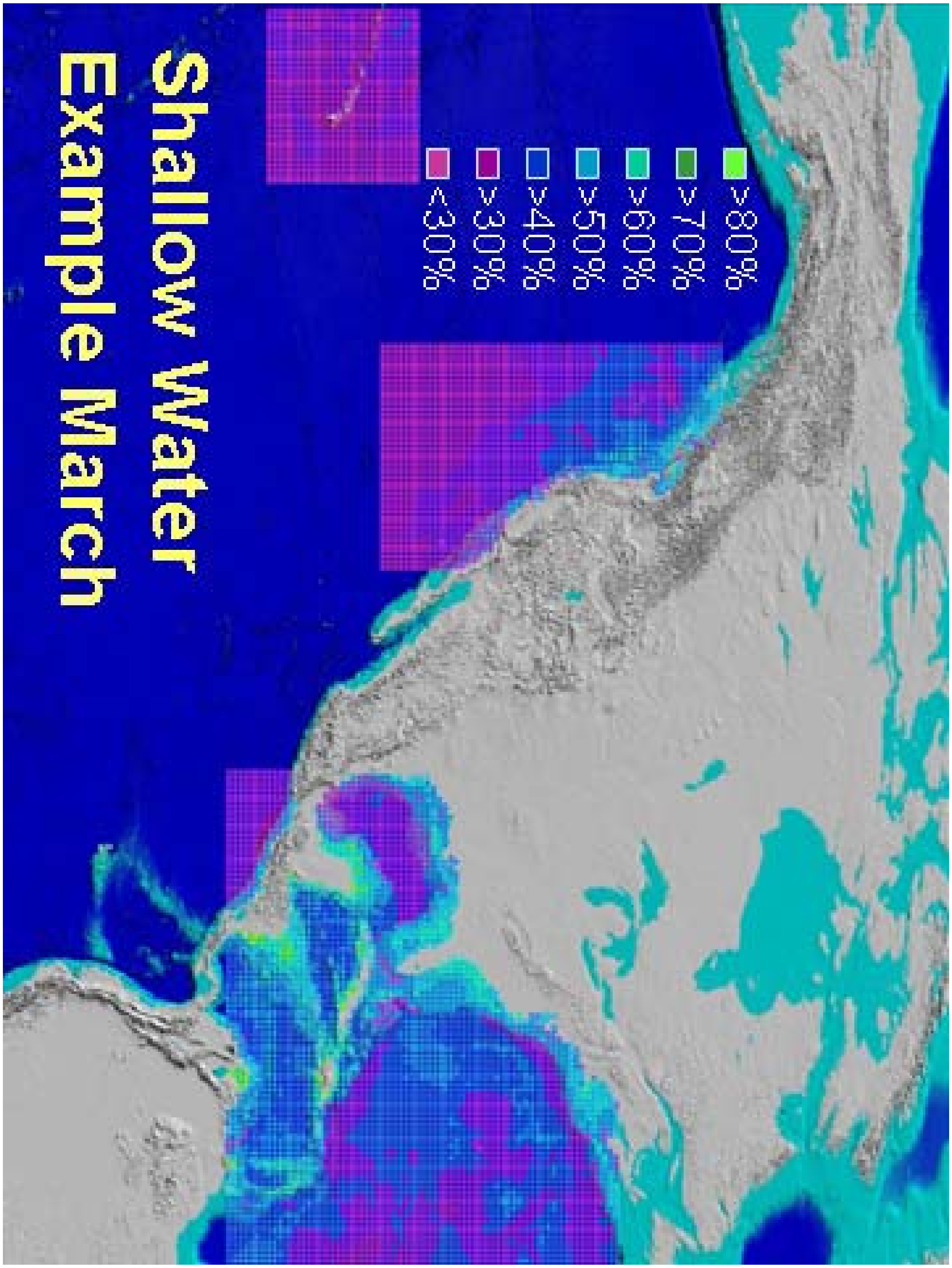

Figure 44. March Shallow Water Color Contoured Match Score. [After ArcIMS].

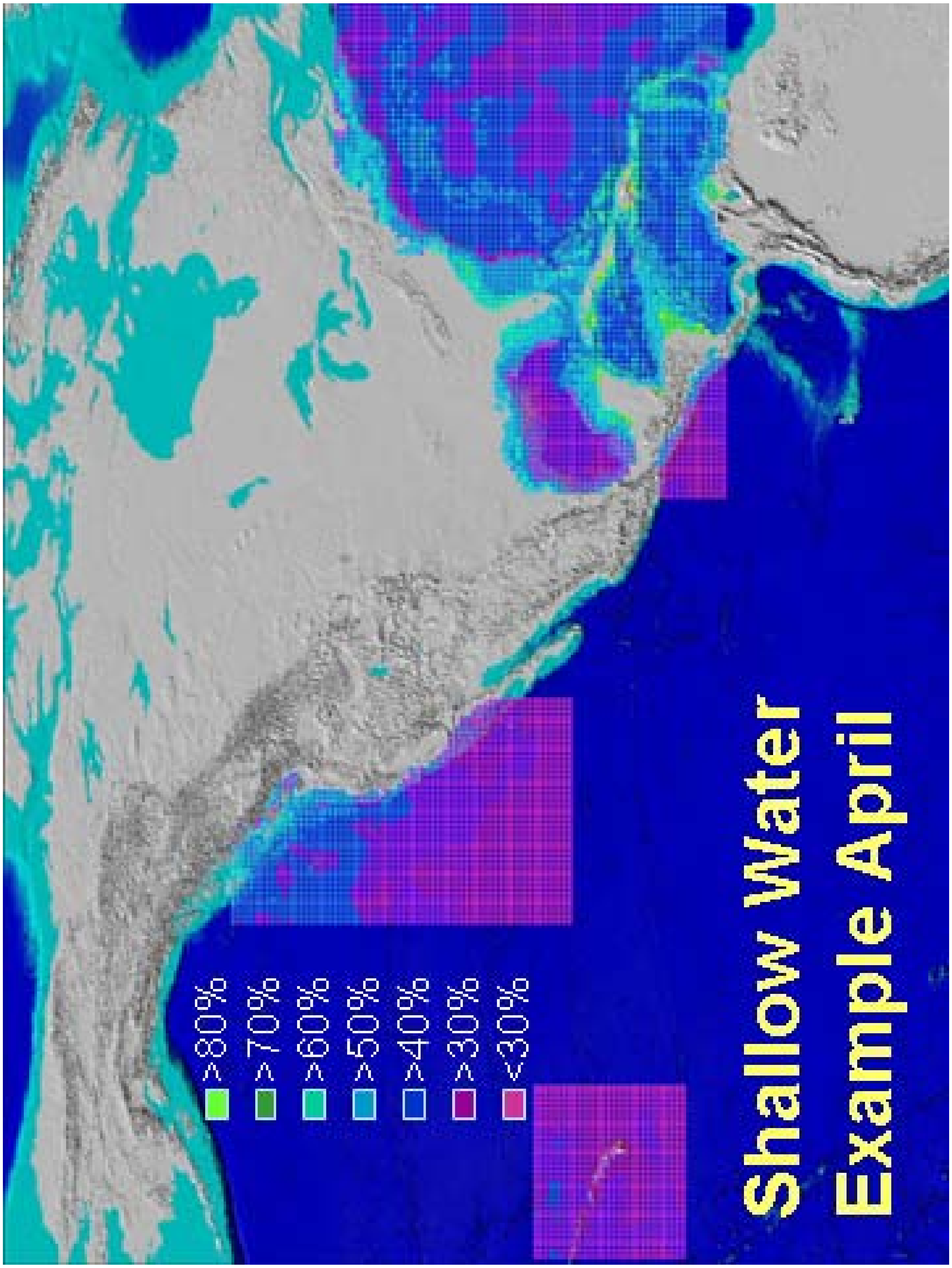

Figure 45. April Shallow Water Color Contoured Match Score. [After ArcIMS].

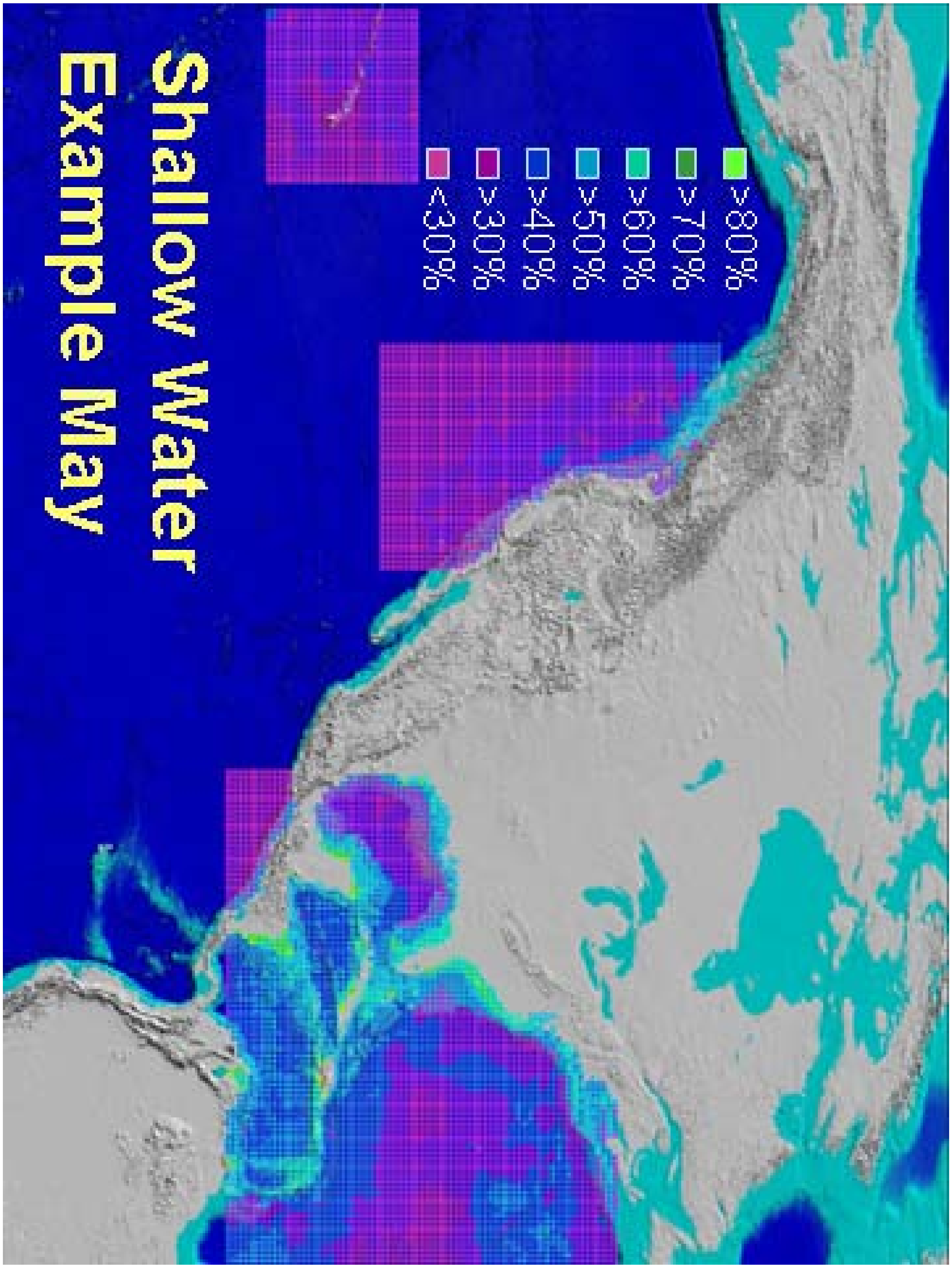

Figure 46. May Shallow Water Color Contoured Match Score. [After ArcIMS].

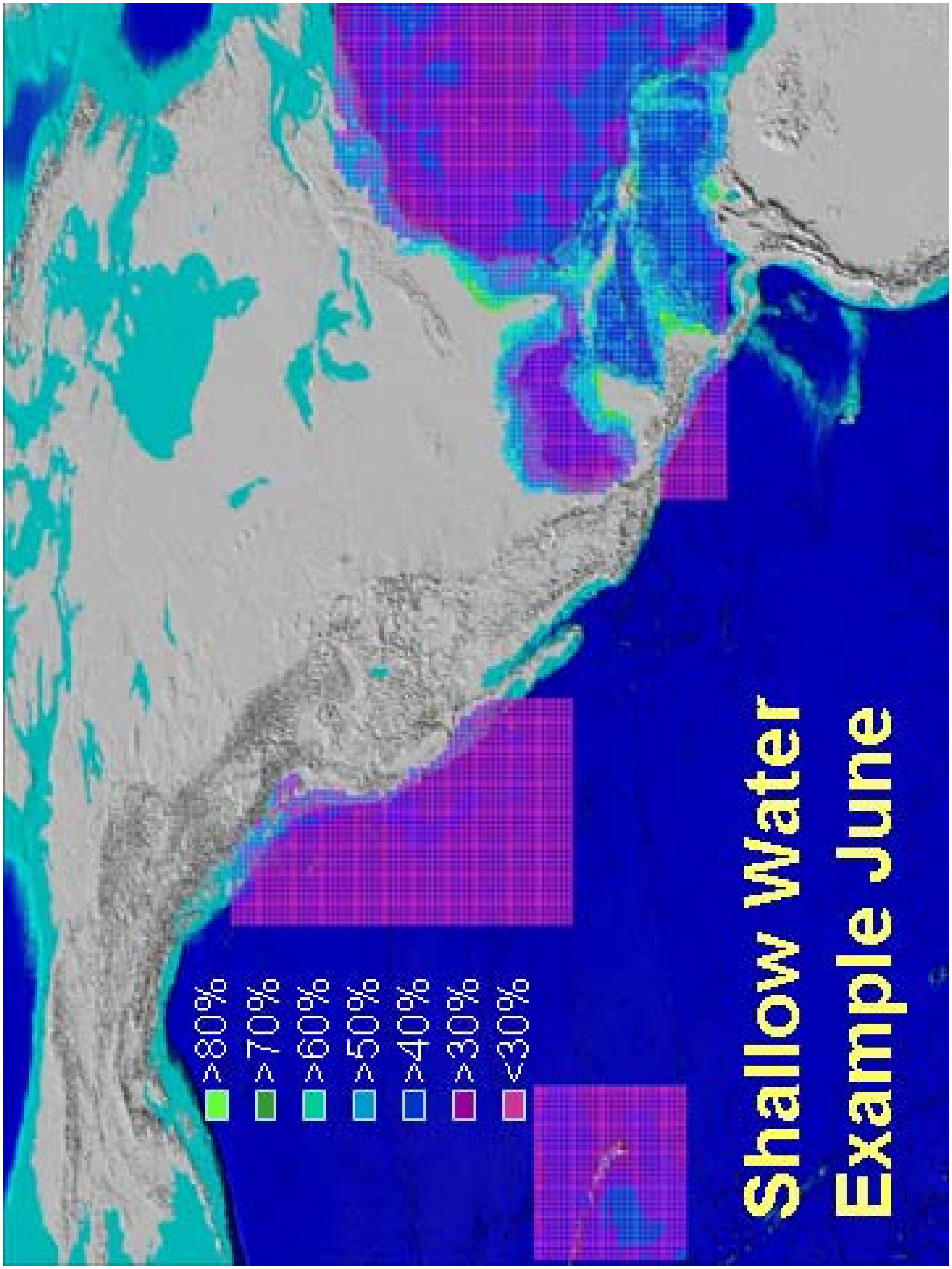

Figure 47. June Shallow Water Color Contoured Match Score. [After ArcIMS].

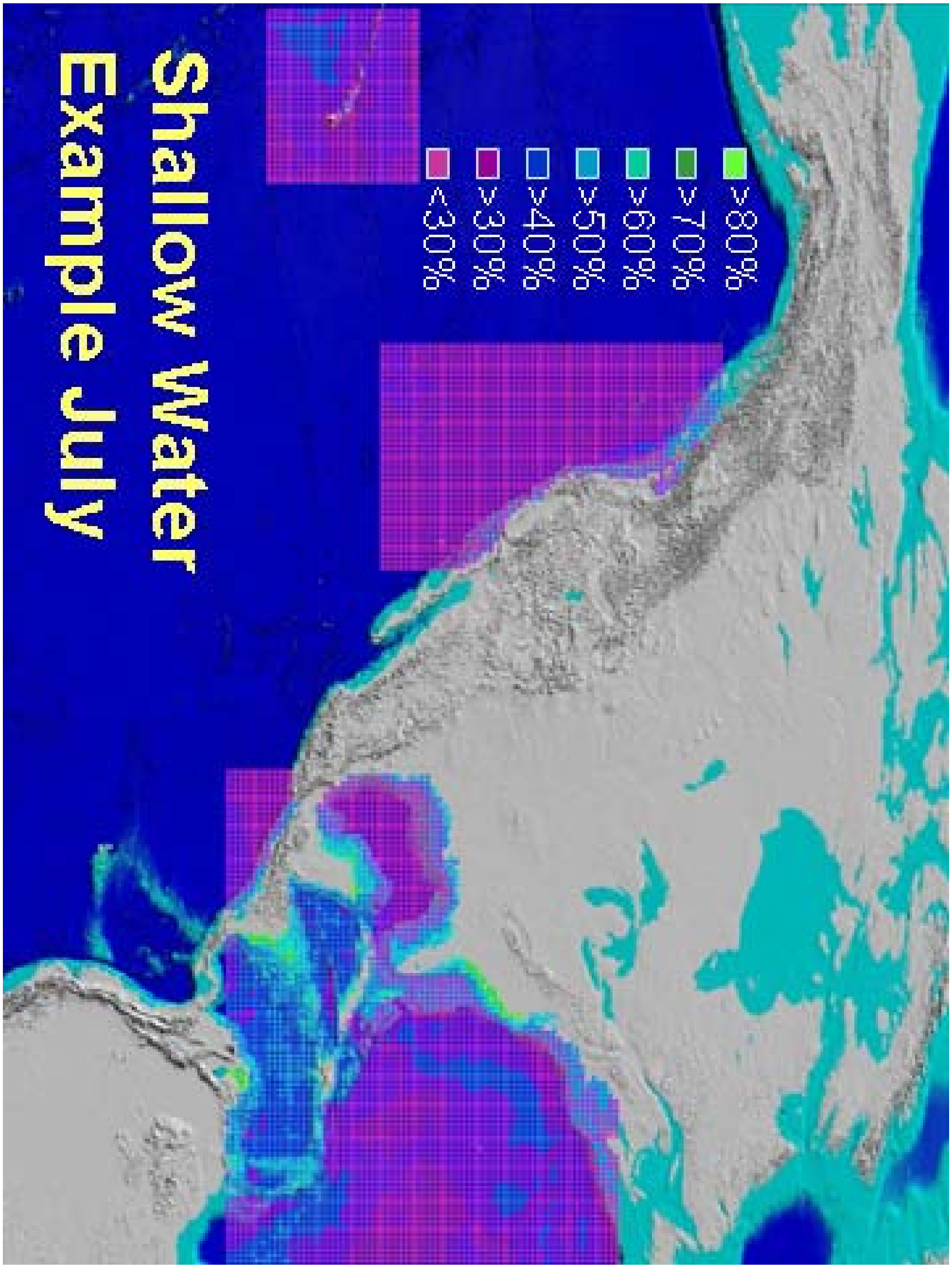

Figure 48. July Shallow Water Color Contoured Match Score. [After ArcIMS].

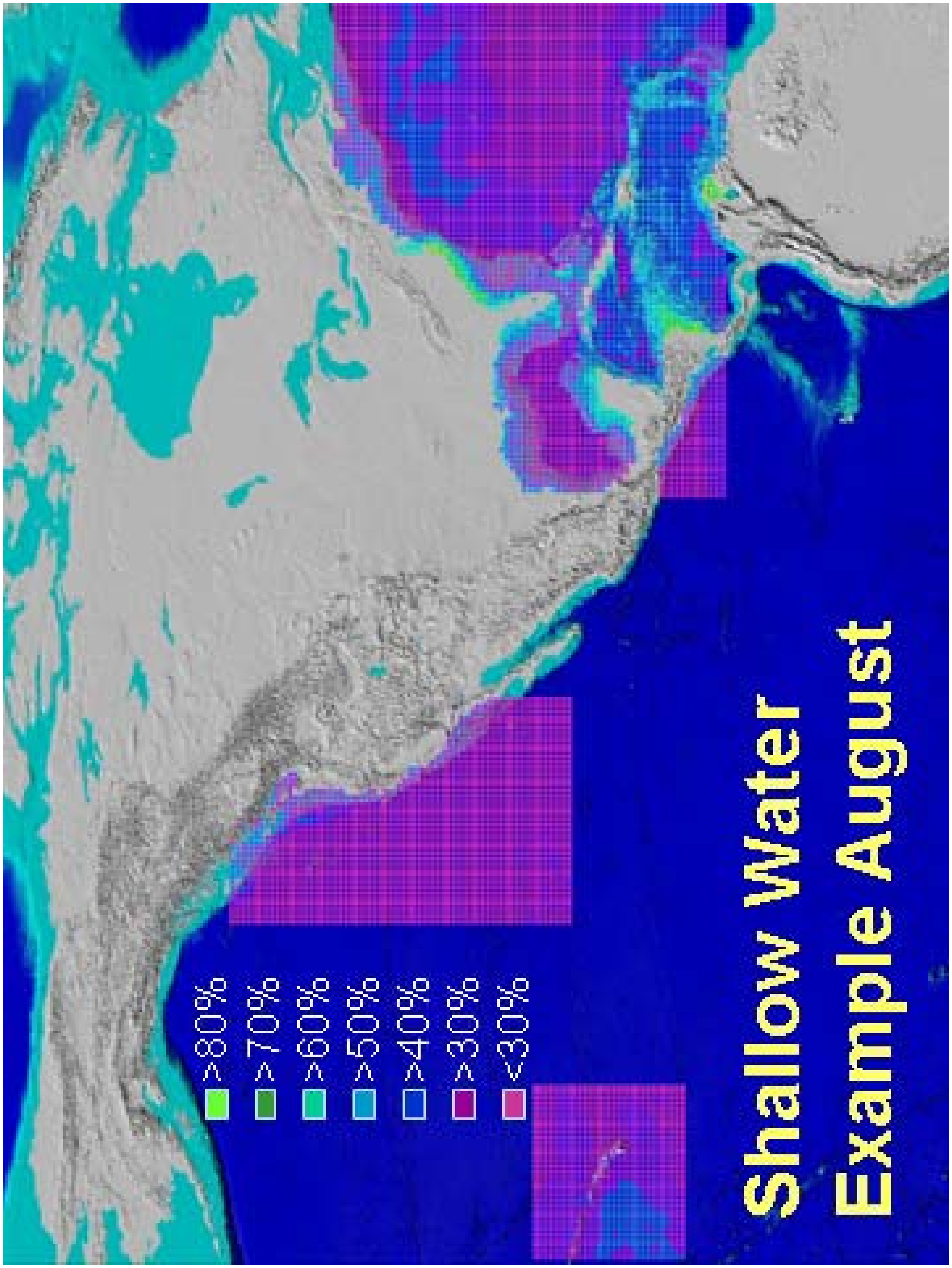

Figure 49. August Shallow Water Color Contoured Match Score. [After ArcIMS].

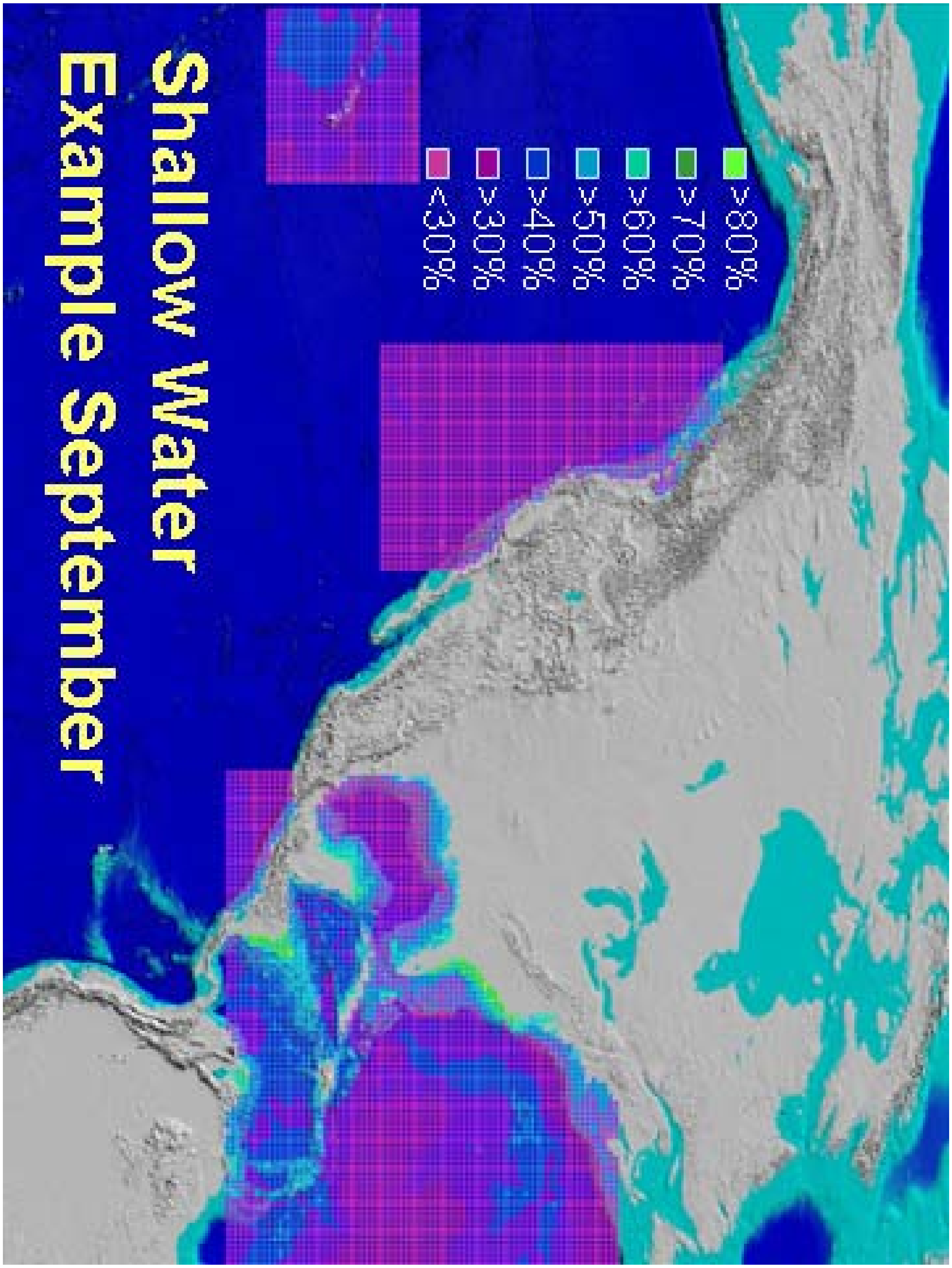

Figure 50. September Shallow Water Color Contoured Match Score. [After ArcIMS].

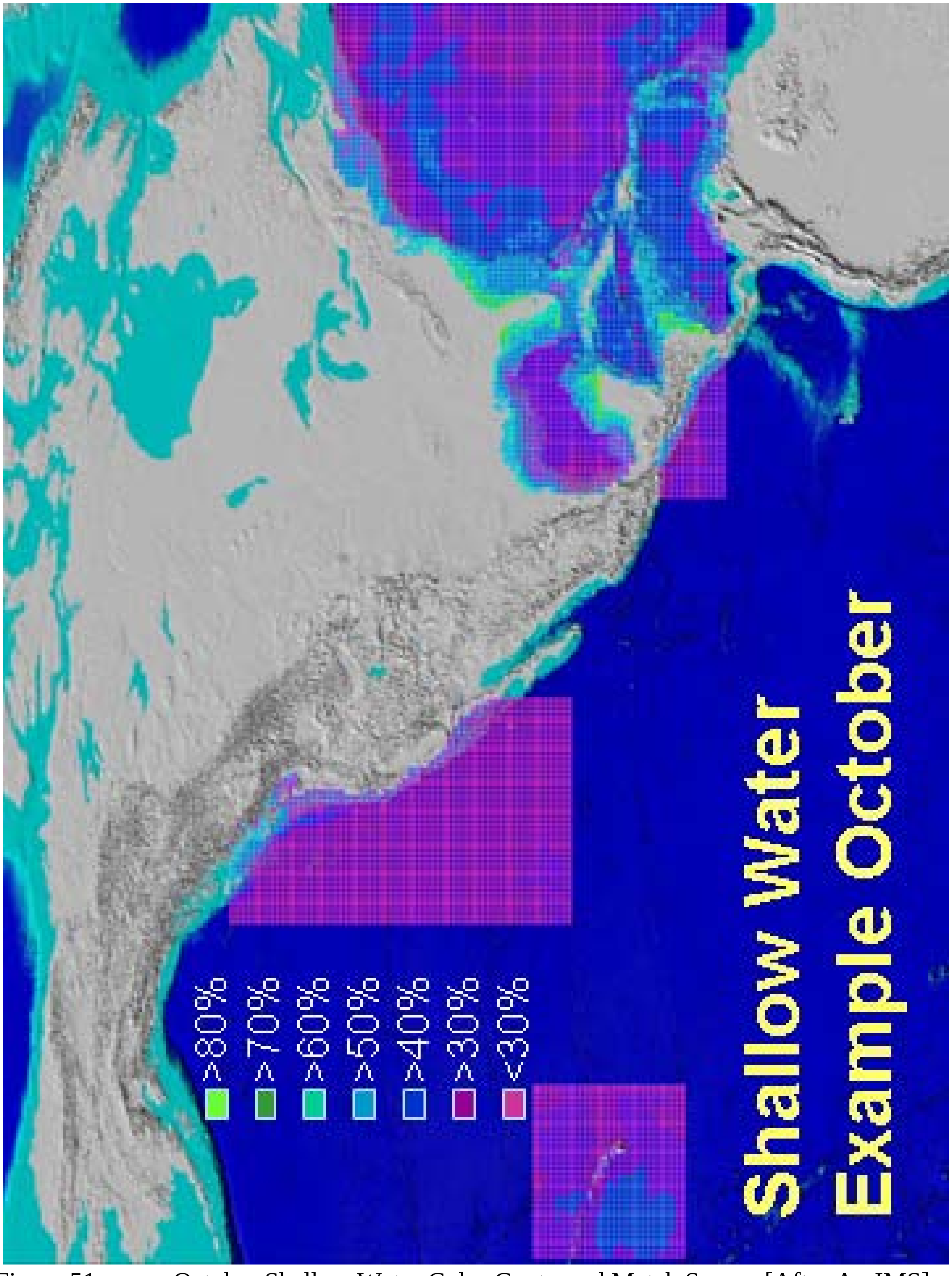

Figure 51. October Shallow Water Color Contoured Match Score. [After ArcIMS].

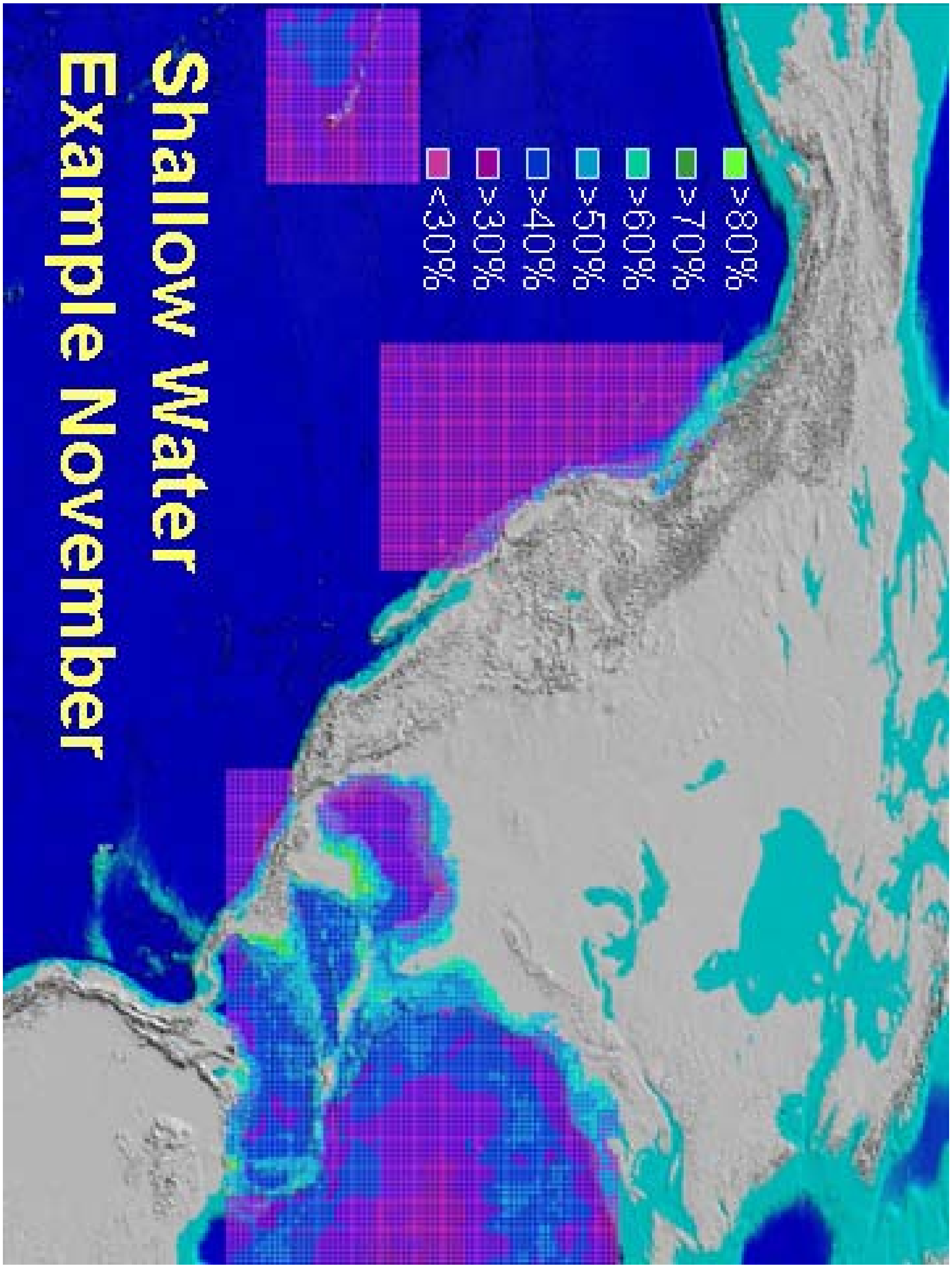

Figure 52. November Shallow Water Color Contoured Match Score. [After ArcIMS].

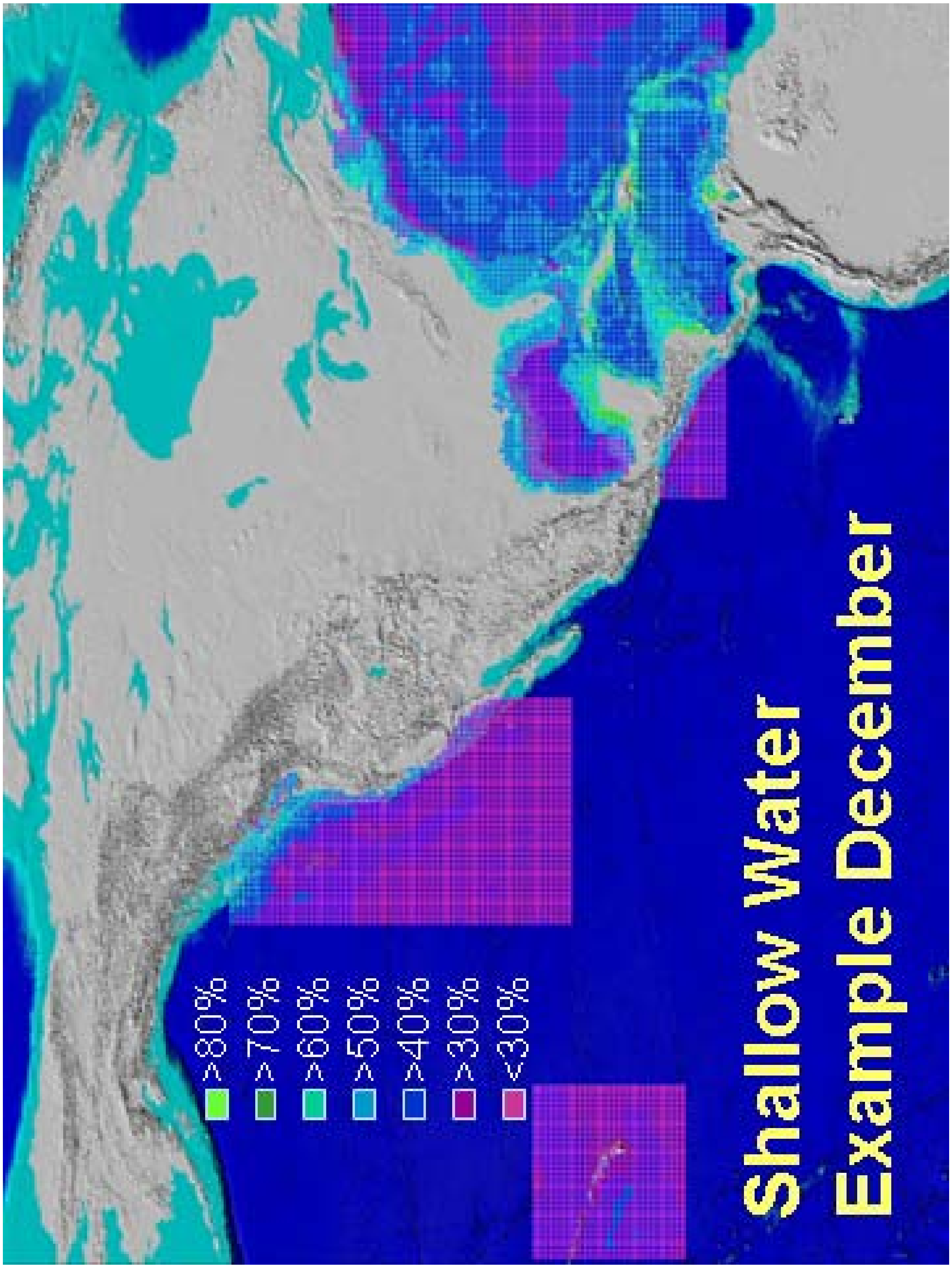

Figure 53. December Shallow Water Color Contoured Match Score. [After ArcIMS].

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LIST OF REFERENCES

Alpers, Werner, Heng Wang-Chen, and Lim Hock, 2005: Observation of Internal Waves in the Andaman Sea by ERS SAR. [Available online at http://earth.esa.int/workshops/ers97/papers/alpers3/]. March 2005.

Apel, John R., James R. Holbrook, Antony K. Liu, and John J. Tsai, 1985: The Sulu Sea Internal Soliton Experiment. Journal of Physical Oceanography 15, 1625-1651

ArcIMS Image Service, 2000: World Shaded Relief . [Available online at http://www.geographynetwork.com by typing "World Shaded Relief" in the "Optional Keyword" space]. April 2005.

Bauer, B. J. and T. Howlett, 1995: *Aerographers Mate 1 & C, NAVEDTRA 14010*, Naval Education and Training Professional Development and Technology Center, 310 pp.

Coleman, Rachel, 2005: Re: New RFS 1/26, February 08, 2005, 2 pp. [Available SIPRNET e-mail from everetkr@nps.navy.smil.mil].

Commander Submarine Development Squadron Twelve, 2004: FY-05 TAC D&E CSDS12 Proposal No 4 ANALOGOUS EXERCISE ENVIRONMENTS, 1p. [Available from Commander Submarine Development Squadron Twelve, Naval Submarine Base New London, Groton CT 06349]

Interview between Cooke, Wil, Sonalyst Systems, Mike Buriangk , Lieutenant Commander, USN, CSDS 12, Tim Cowen, Civilian, CSDS 12, Rick Diaz, Lieutenant Commander, USN, CSDS 12, David W. Harvey, CSDS 12 N714, Pete Lorenz, Naval Warfare Development Command, Jason Perusek, Lieutenant, USN, CSDS 12, Chuck Young, Civilian, CSDS 12, and the author, 07 December 2004.

ESRI, 2002: ArcMap Version 8.3 (Build 800). ESRI Inc.

Global Temperature-Salinity Profile Program, cited 2005: Global Temperature-Salinity Profile Program. [Available online at http://www.nodc.noaa.gov/GTSPP/gtspp-home.html]. March 2005.

Godin, O.A., and D.M.F. Chapman, 1999: Shear-speed gradients and ocean seismo-acoustic noise resonances, J. Acoust. Soc. Am. 106, 2367-2382.

Hsu, M. K., and A. K. Liu, 2000: Nonlinear internal waves in the South China Sea, Canadian J. Rem. Sens., 26, 72-81

Kara, A. B., P. A. Rochford, and H. E. Hurlburt, 2000: An optimal definition for ocean mixed layer depth. *J. Geophys. Res.*, **105**, 16 803-16 821.

Kosko, Bart, 1993: *Fuzzy Thinking the New Science of Fuzzy Logic*. Hyperion, 318 pp.

Math Works Inc, The, 2003: MATLAB Version 6.5.1.199709 Release 13 (Service Pack 1). The Math Works Inc.

McGee, Timothy, 2005: Enterprise Strategy, Memorandum Ser 8/008, 10pp. [Available from Commander Naval Meteorology and Oceanography Command, 1100 Balch Blvd., Stennis Space Center, MS 39529-5005]

Medwin, Herman and Clay, Clarence S., 1998: *Fundamentals of Acoustical Oceanography*, Academic Press, 712 pp.

Miyamoto, Robert, 1999: Environmental Site Analyzer Version 3.1, Applied Research Laboratory, University of Washington.

National Geophysical Data Center, cited 2005a: 2-Minute Gridded Global Relief Data (ETOPO2). [Available online at http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html]. March 2005.

________, cited 2005b: NGDC Coastal Relief Model. [Available online at http://www.ngdc.noaa.gov/mgg/coastal/coastal.html]. March 2005.

________, Cited 2005c: Seafloor Sediment Grain Size Database NGDC Data Set G00127. [Available online athttp://www.ngdc.noaa.gov/mgg/geology/size.html]. March 2005.

________, cited 2005d: Total Sediment Thickness of the World's Oceans & Marginal Seas. [Available online at http://www.ngdc.noaa.gov/mgg/sedthick/sedthick.html]. March 2005.

________, cited 2005e: World Data Center for Marine Geology & Geophysics, Boulder Marine Trackline Geophysics. [Available online at http://www.ngdc.noaa.gov/mgg/geodas/trackline.html]. March 2005.

National Ocean Data Center, cited 2005a: World Ocean Atlas 2001. [Available online at http://www.nodc.noaa.gov/OC5/WOA01/pr_woa01.html]. March 2005.

________, cited 2005b: World Ocean Database 2001. [Available online at http://www.nodc.noaa.gov/OC5/WOD01/pr_wod01.html]. March 2005.

National Ocean Service, cited 2005: Hydrographic Survey Data. [Available online at http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html]. March 2005.

Naval Oceanographic Office, cited 2005a: Classified Data Warehouse [Available online at http://199.208.205.53/index.html]. March 2005.

________, cited 2005b: DBDBV Version 4.2. [Available online at https://128.160.23.42/dbdbv/dbvquery.html]. March 2005.

________, cited 2005c: Generalized Digital Environmental Model Variable Extraction. [Available online at https://128.160.23.42/gdemv/gdemv.html]. March 2005.

Naval Oceanographic Office Systems Integration Division, 1993: Data Base Description for Wind and Residual Noise (WRN). [Available online at http://199.208.205.46/products/OAML/WRN_2.1/OAML-DBD-16B_Feb_1993_(U)/wrn.htm#INTRODUCTION]. March 2005.

________, 2001a: Data Base Description for High-Frequency Bottom Loss (HFBL). [Available online at http://199.208.205.46/products/OAML/HFBL_2.2/OAML-DBD-11C_Feb_2001_(U)/default.htm]. March 2005.

________, 2001b: Data Base Description for Low-Frequency Bottom Loss (LFBL). [Available online at http://199.208.205.46/products/OAML/LFBL_10.0/OAML-DBD-12K_Feb_2001_(U)/title.htm]. March 2005.

________, 2004: *Oceanographic and Atmospheric Master Library Summary*, 112 pp. [Available from Naval Oceanographic Office, Stennis Space Flight Center, Mississippi 39522-5001]

Naval Pacific Meteorology and Oceanography Center, San Diego, 2005: Shapefiles of Operating Areas and Airspace Warning Areas. [Available from dbreeder@nps.edu]

Naval Pacific Meteorology and Oceanography Detachment, Kaneohe Bay, Hawaii, cited 2005: Acoustic Propagation Paths. [Available online at http://www.npmoc.navy.mil/KBay/acousticpaths.htm]. March 2005.

Naval Research Laboratory Code 7304, cited 2005: Naval Research Laboratory (NRL) Mixed Layer Depth (NMLD) Climatology. [Available online at http://www7320.nrlssc.navy.mil/nmld/nmld.html]. March 2005.

Naval Research Laboratory Division 7300, cited 2005: MODAS Hompage. [Available online at http://www7300.nrlssc.navy.mil/altimetry/]. March 2005.

NRaD Naval Surface Warfare Center, 1995: Interactive Multisensor Analysis Trainer for the Personal Computer (PCIMAT) Version 3.0. Naval Surface Warfare Center.

Urick, Robert J., 1983: *Principles of Underwater Sound*. 3rd Edition, Peninsula Publishing, 423 pp.

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